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Impact of selenium nanoparticles on plant stress tolerance: a comprehensive review

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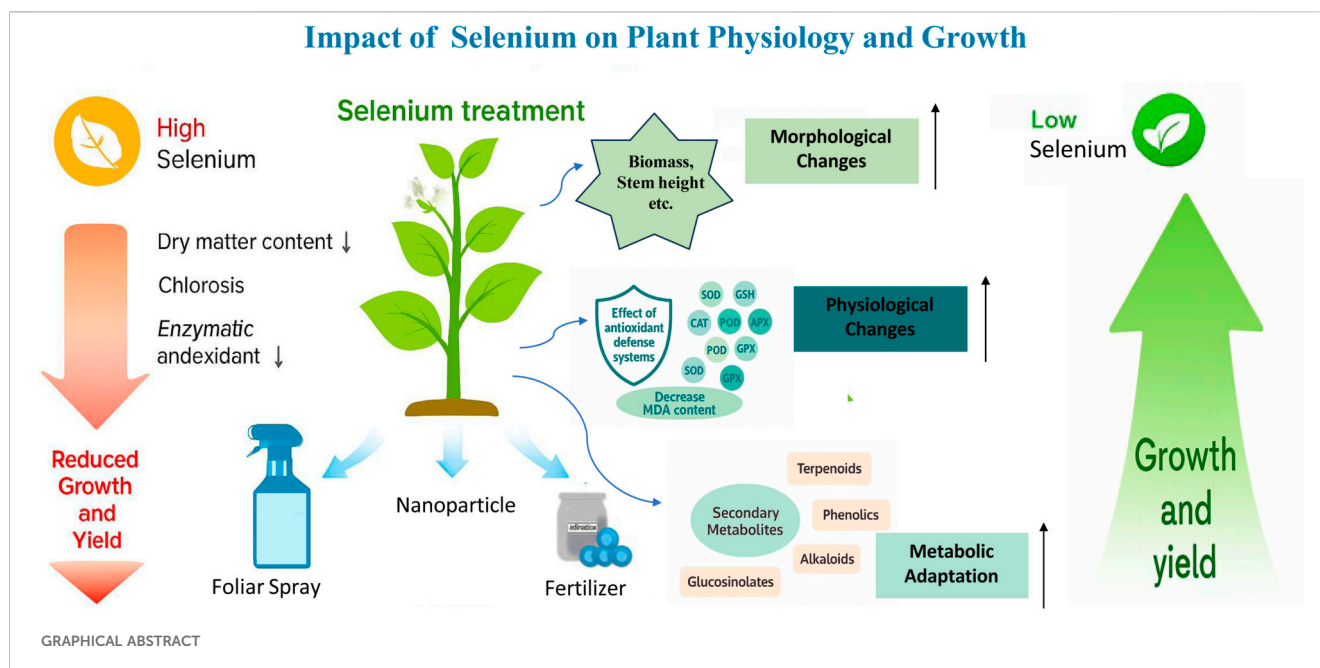
Selenium (Se), initially perceived mostly as a harmful element, is now recognised as an effective trace nutrient that promotes plant growth and stress resilience. Though not vital for most plant species, adequate Se concentrations may increase photosynthesis, activate antioxidant defence mechanisms, and improve tolerance to various biotic and abiotic stressors. The application of selenium nanoparticles (SeNPs) has been proposed because they exhibit greater bioavailability, higher stability, and lower toxicity compared to inorganic selenium forms, and recent advances in nanotechnology have enabled their efficient synthesis. SeNPs are readily internalised by plants, where they promote growth, regulate osmotic balance, activate stress-responsive genes, and strengthen plant defence mechanisms while minimising pollution. Current research highlights the role of Se and SeNPs in regulating redox homeostasis, secondary metabolite biosynthesis, and defence signalling networks. This review synthesises recent findings on Se speciation, uptake pathways, metabolic incorporation, and the diverse physiological roles of SeNPs in improving crop resilience. Future studies must rely on clarifying the molecular mechanisms, determining optimal application strategies, and integrating SeNPs into sustainable agricultural practices to enhance productivity and stress tolerance, thereby addressing concerns over food security under the impacts of climate change.

KEYWORDS

nano selenium, plant health, selenium, stress tolerance, uptake mechanism

1 Introduction

The continuous increase in the world's population has increased demand for higher food production, thereby exerting a considerable burden on agriculture resources. Factors such as shrinking arable land, soil degradation, prolonged droughts, climate variability, and excessive use of chemical inputs have contributed to declining crop yields worldwide (Benbrook et al., 2021; Goulson, 2014). To address these pressing challenges, strategies that enhance crop productivity while reducing environmental burdens need to be developed. Nanotechnology has been recognised as a transformative tool in this regard, offering potential innovations often described as the new phase of the 'green revolution' (Lowry et al., 2019). Nanoparticles (NPs) are generally defined as resources that have at least one structural dimension below 100 nm (Khan et al., 2019). Their nanoscale features confer unique physicochemical properties that facilitate close interactions with plant systems. Importantly, they can pass through plant cell walls because of their small size exclusion limits (5–20 nm), thereby acting as efficient vehicles for nutrient delivery and absorption (Schwab et al., 2016). The use of nanofertilizers, a subclass of NPs that contain essential



nutrients, illustrates this potential, as they release nutrients under regulated conditions, improving nutrient-use efficiency in contrast to traditional fertilizers (Kah et al., 2018). These advances have been driven by interdisciplinary progress in chemistry, physics, biology, and materials science (Narayanan and Sakthivel, 2010).

Among emerging nanomaterials, selenium nanoparticles (SeNPs) have increasing fascination in agriculture research because of their positive action towards crop growth and stress resilience. Selenium (Se), once thought to be harmful, is now considered a positive element that enhances photosynthesis, modulates antioxidant defence mechanisms, and stabilises cellular membranes (Hasanuzzaman et al., 2020a; Khan et al., 2023). The chemical form and mode of application are critical, as excessive accumulation may exert phytotoxic effects (Hussein et al., 2019). Compared to inorganic selenium compounds, SeNPs are characterised by higher bioavailability, improved stability, reduced toxicity, and enhanced compatibility with plant tissues (Wadhvani et al., 2016; Skalickova et al., 2017). In agriculture, SeNPs serve a variety of purposes by reducing abiotic stressors such as heat, drought, salt, and heavy metal toxicity, strengthening tolerance to biotic stress (Qin et al., 2025). They can influence fundamental physiological mechanisms, like photosynthesis, hormone signalling, nutrient uptake, and secondary metabolism, ultimately promoting crop growth and resilience (Hussein et al., 2019). Selenium levels differ significantly among vegetable crops, altering their nutritional value and physiological responses. The plants like cabbage and mushrooms have relatively high selenium levels, but asparagus and tomatoes have moderate to low quantities (Table 1). Understanding natural variability is vital for determining the effects of selenium nanoparticles on plant stress tolerance and metabolic regulation.

A literature survey using PubMed, Scopus, and Google Scholar reveals a rapid rise in studies on the influence of selenium nanoparticles (SeNPs) in plant stress tolerance over the past decade. Before 2015, less than ten papers were published;

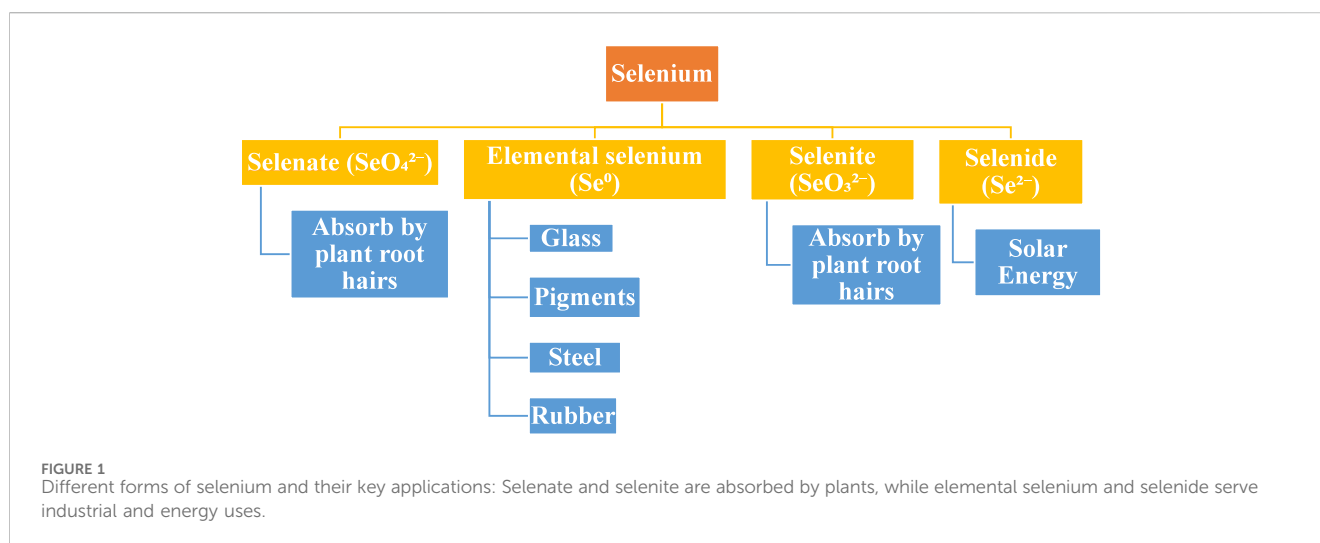
whereas between 2015 and 2025, more than 80 research and review articles have appeared, with over 60% published in the last 5 years (Qin et al., 2025). This growing quantity of literature not only highlights the emerging importance of SeNPs in agricultural nanotechnology but also suggests that, despite the increasing number of studies, mechanistic insights and long-term field evaluations remain comparatively limited, underscoring the need for more focused research in this promising area. Unlike previous reviews, which mostly focused on SeNP synthesis and general plant responses, this paper offers a mechanistic and integrative assessment of SeNP-mediated stress tolerance across biotic and abiotic conditions. It emphasises the dose-dependent duality, safe toxic thresholds, and growing epigenetic and transgenerational impacts of SeNP exposure. This comprehensive review aims to fill knowledge gaps by providing an integrated perspective on selenium chemistry, plant physiological functions, and selenium nanoparticle synthesis, highlighting agricultural applications and guiding future research directions for the sustainable use of SeNPs in plant stress biology.

2 Selenium speciation and soil chemistry

Soil Se is derived from natural sources, such as geology and atmospheric deposition, as well as human-extractive operations like mining and burning fossil fuels (Zhang et al., 2025). Bioavailability is also largely dependent on chemical speciation, soil pH, and redox conditions (Fox et al., 2002). The major selenium species are selenate (SeO_4^{2-}), selenite (SeO_3^{2-}), elemental selenium (Se^0), and selenide (Se^{2-}) (Figure 1). Selenate is easily absorbed by plants and is more mobile in soils. Selenite is also more prevalent in acidic soils than selenate and in anaerobic zones, where it is relatively immovable (Szöllősi et al., 2022). Microbial biotransformation of selenium

TABLE 1 Selenium profile in various vegetable crops (Fox et al., 2002).

Vegetable crop	Selenium content (mg/100 g)	Insights
Cabbage	20–30	High in inorganic selenium
Carrots	10–15	Contains both inorganic and organic selenium forms
Tomatoes	5–10	High in organic selenium (selenomethionine)
Green peas	5–10	Contains organic selenium in seeds
Asparagus	3–5	Moderate selenium content
Mushrooms	15–36	Shiitake mushrooms have the highest selenium content among vegetables



is significant in the selenium cycle, where bacteria and fungi convert selenium from one form to another, affecting its availability and toxicity in soil (Zhang et al., 2023). Exploiting such soil-microbe relationships is an attractive approach to promote the bioavailability of selenium in crops.

2.1 Selenium metabolism

The metabolism of selenium (Se) establishes its dispersion across different parts and stages of plant development. In a study by Pickering et al. (2000), spatially resolved X-ray absorption spectroscopy was employed to demonstrate that selenate (SeVI) primarily accumulates in mature leaves, while organic Se compounds (Figure 2), notably methylselenocysteine, are enriched in the young leaves of the hyperaccumulator *Astragalus bisulcatus*.

2.1.1 Conversion of selenate to selenite and selenide

Selenium assimilation in plants begins with the absorption of selenate (SeVI) through the sulfate assimilation pathway, which primarily occurs in chloroplasts. SeVI is then reduced to selenite (SeIV) and subsequently to selenide (Se²⁻), with this reduction step being both crucial and limiting in the overall process of selenomethionine production.

Two key enzymes facilitate the transformation of SeVI to SeIV: ATP sulfurylase (APS), which facilitates the formation of adenosine phosphoselenate (APSe) from SeVI and ATP. This is a result of adenosine phosphosulfate reductase (APR), which reduces APSe to SeIV. During this process, APSe can also be phosphorylated to form phosphor adenosine phosphoselenate (PAPSe) via APS kinase, potentially diverting it toward secondary metabolite synthesis. APS and APR isoforms in the cytosol and chloroplasts; however, chloroplasts remain the primary site of SeVI reduction. While SeVI is primarily transported to the shoots for further assimilation, SeIV tends to be quickly metabolised in the roots, with limited movement.

2.1.2 Selenite to selenocysteine

SeIV is transformed into selenocysteine (SeCys) via enzymatic and non-enzymatic pathways. In the non-enzymatic reduction process, SeIV reacts with glutathione (GSH) to form selenodiglutathione (GS–Se–SG), which is decreased by NADPH to produce glutathioneselenol (GS–SeH). GS–SeH subsequently reacts with O-acetylserine (OAS) to produce SeCys, which transferred into cytosol (Terry et al., 2000). SeIV can be converted to selenide (Se²⁻) with the action of sulfite reductase (Benjamin et al., 2012) or through non-enzymatic reduction facilitated by glutathione (GSH). Subsequently, cysteine synthase, a combination of serine acetyltransferase and OAS-thiol lyase, transforms Se²⁻ + OAS into SeCys. Moreover, the direct transformation of SeIV into SeCys by

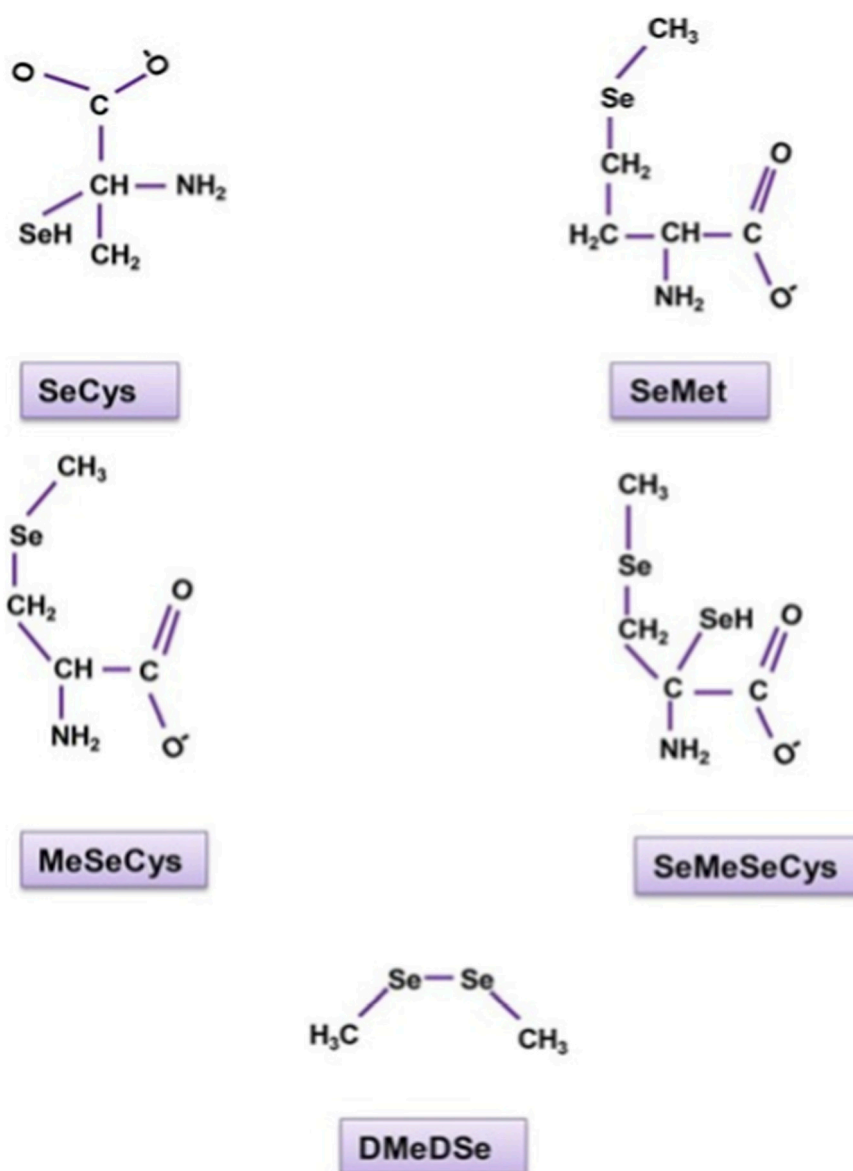


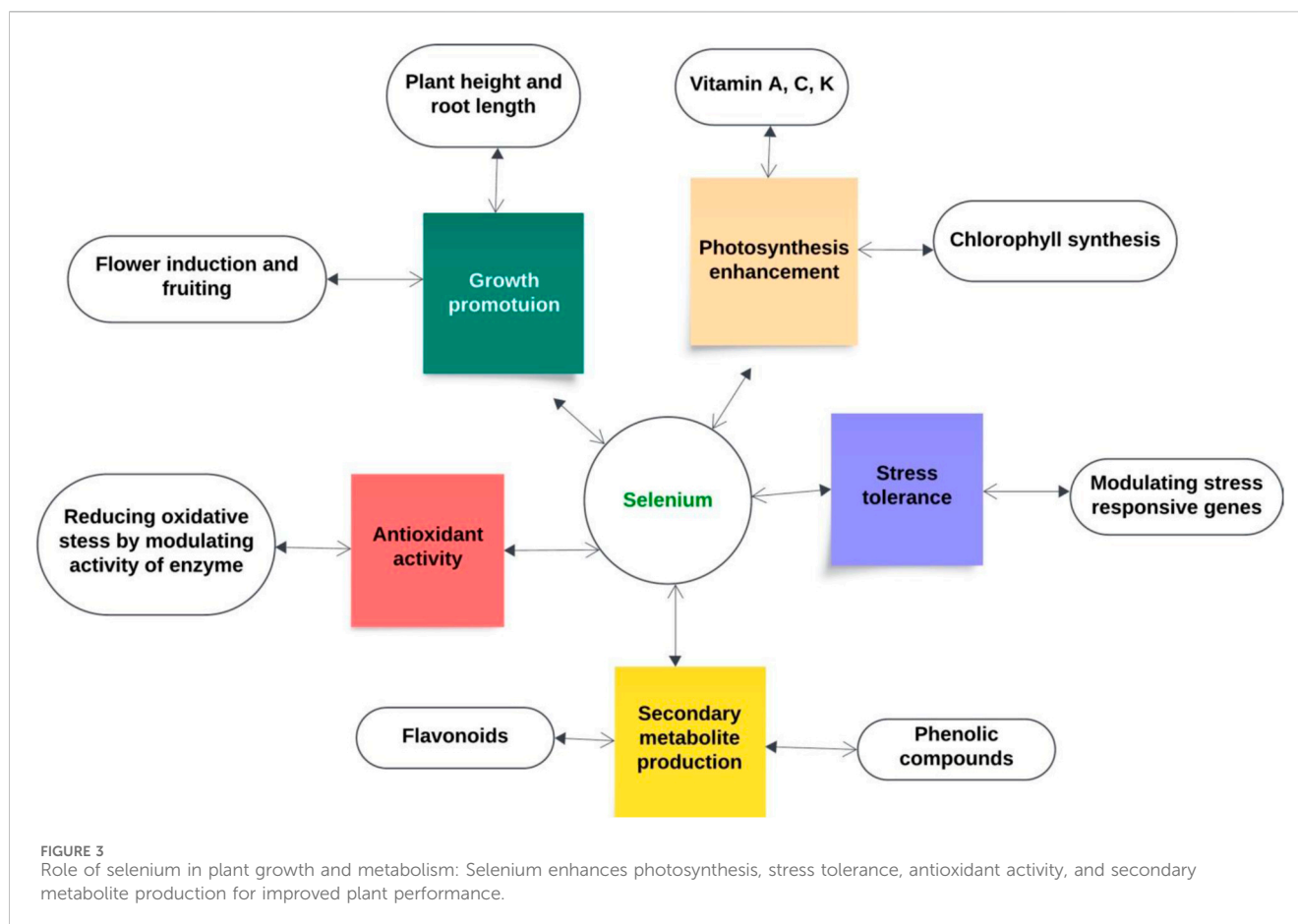
FIGURE 2
Structural features of major organoselenium compounds: Includes SeCys, SeMet, MeSeCys, SeMeSeCys, and DMeDSe, showing variations in selenium bonding and functional groups.

selenomethyltransferase (SMT) has been reported (Pilon-Smits and Quinn, 2010).

2.1.3 SeCys metabolism and diversification of Se-Metabolites

SeCys acts as a central point for various transformations in the body. SeCys lyase breaks down SeCys into elemental selenium (Se^0) and alanine, thereby decreasing toxicity, as Se^0 is less biologically reactive (Pilon-Smits and Quinn, 2010). Another route involves the methylation of SeCys by SeCys methyltransferase (SeCysMT), resulting in the formation of MeSeCys (Shahid et al., 2019). MeSeCys further move into S-methylselenogluthathione (S-MeSeGS) through methionine γ -lyase; γ -glutamylmethylselenocysteine (γ -GluMeSeCys) via

γ -glutamylcysteine synthetase, which is a primary storage form in *Astragalus* spp. (Freeman et al., 2007; Gupta and Gupta, 2016) and volatile dimethyl diselenide (DMDSe). As noted by Chauhan et al. (2019), SeCys is involved in several metabolic pathways. It can combine with O-phosphohomoserine to produce selenohomocysteine (SeHCys) through selenocystathionine, facilitated by cystathionine γ -synthase and β SeHCys, which can then react with OAS to create selenohomolanthionine (SeHLan) (Pilon-Smits and Quinn, 2010). Alternatively, SeHCys are transformed into ssselenomethionine (SeMet) by methionine synthase, followed by methylation to produce methyl-SeMet (MeSeMet). There are two possible pathways for MeSeMet metabolism: (i) decarboxylation and transamination to



generate dimethyl selenopropionate (DMSeP), which is then cleaved by DMSeP lyase to form volatile DMSe, and (ii) direct conversion by methylmethionine hydrolase (Bodnar et al., 2012). These metabolic pathways play a role in minimizing or preventing the non-specific incorporation of SeCys and SeMet into proteins, thereby reducing Se toxicity. Additionally, in the cytosol, SMT may convert SeCys to MeSeCys, which can be oxidised to methyl-SeCys-selenoxide (MeSeCysSeO). This compound is then cleaved by cysteine sulfoxide lyase, producing methaneselenol, which is eventually volatilized as DMDS (Bodnar et al., 2012).

3 Selenium in plants

Selenium (Se) supports photosynthesis by protecting chlorophyll and carotenoids, stabilising RuBisCO and photosystems. The activity of enzymes like SOD, CAT, APX, and GR is increased, improving antioxidant defence and reducing ROS damage. Se enhances resistance to abiotic stress by regulating phytohormones, maintaining membrane and nutrient balance, and inducing phytochelatin, while enhancing biotic resistance through pathogen inhibition, activation of defence genes, and phenolic biosynthesis. At optimal levels, it promotes germination, growth, and biomass, although excess levels can cause toxicity (Figure 3).

3.1 Selenium uptake and transport mechanisms in plants

The biological effect of selenium nanoparticles (SeNPs) in plants is dose-dependent, with low concentrations acting as beneficial micronutrients, promoting growth and antioxidant defence, and higher concentrations inducing oxidative and cytotoxic stress. According to Ramos et al. (2023), SeNPs at 10–50 mg L⁻¹ improve germination, photosynthetic efficiency, and ROS-scavenging enzyme activity in crops including *Brassica napus*, *Oryza sativa*, and *Triticum aestivum*. Excessive Se exposure (>100 mg L⁻¹) causes accumulation, alteration of chloroplast ultrastructure, and suppression of primary metabolism, indicating phytotoxicity (Zhou et al., 2021). This dual-phase response correlates with the typical Se behaviour, in which the element changes from an essential micronutrient to a pro-oxidant at high levels. Nanoparticle physicochemical parameters, such as particle size, surface charge, and coating, all influence bioavailability and internal transit within root and leaf tissues, modulating the toxicity threshold. SeNPs at low-to-moderate concentrations are a promising technique for Se biofortification and abiotic stress reduction; however, precise dose optimisation is required to avoid oxidative damage and genotoxicity.

Plants take up selenium mostly as selenate by sulfate transporters, and as selenite through phosphate transporters, with the former having higher mobility and being moved to the shoots (Khan et al., 2019; Liang et al., 2019; Chauhan et al., 2019) (Figure 4).

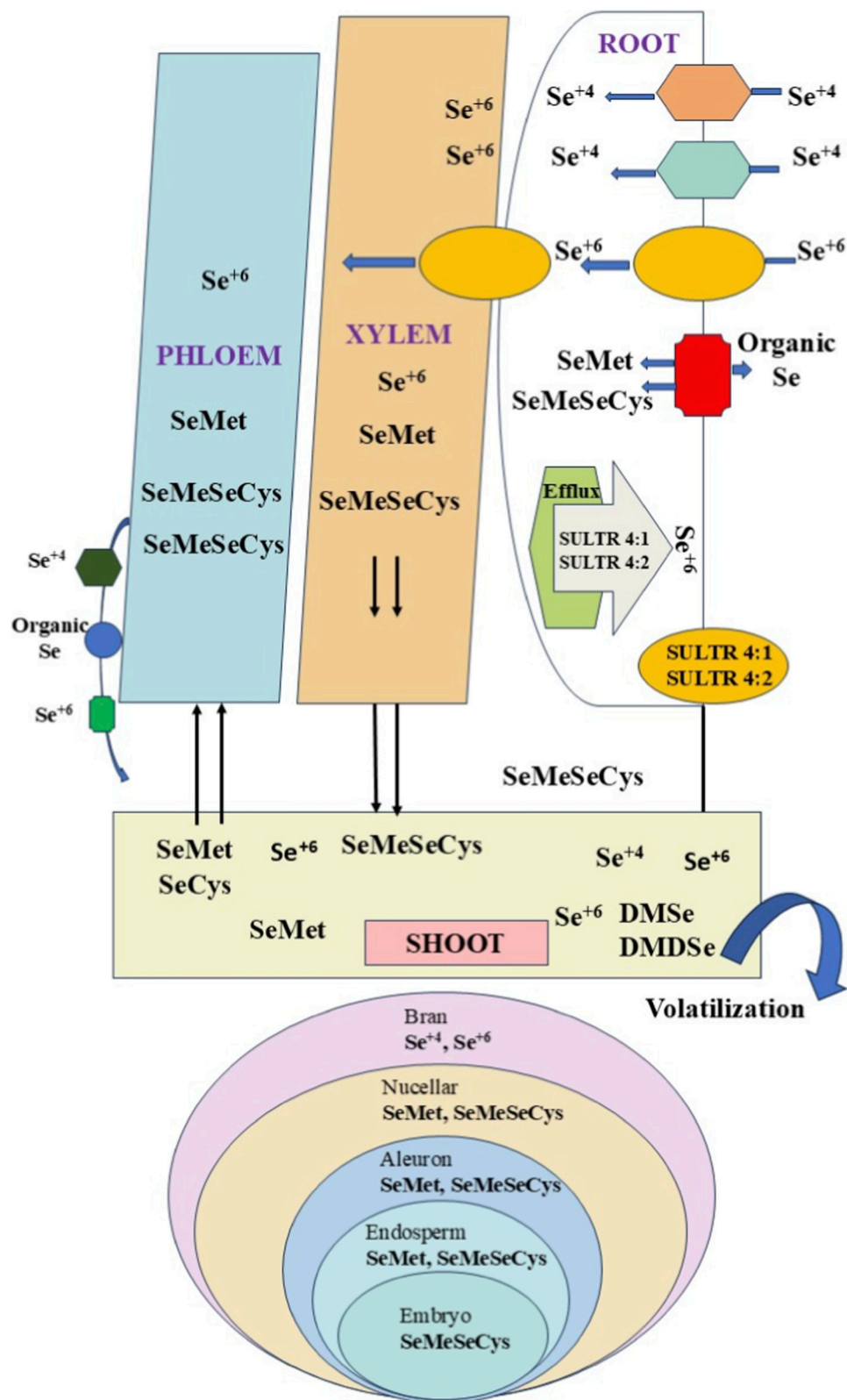


FIGURE 4 Schematic flow diagram illustrating the transporters responsible for the uptake and movement of various selenium species through the xylem and phloem, ultimately reaching the rice grains (Chauhan et al., 2019).

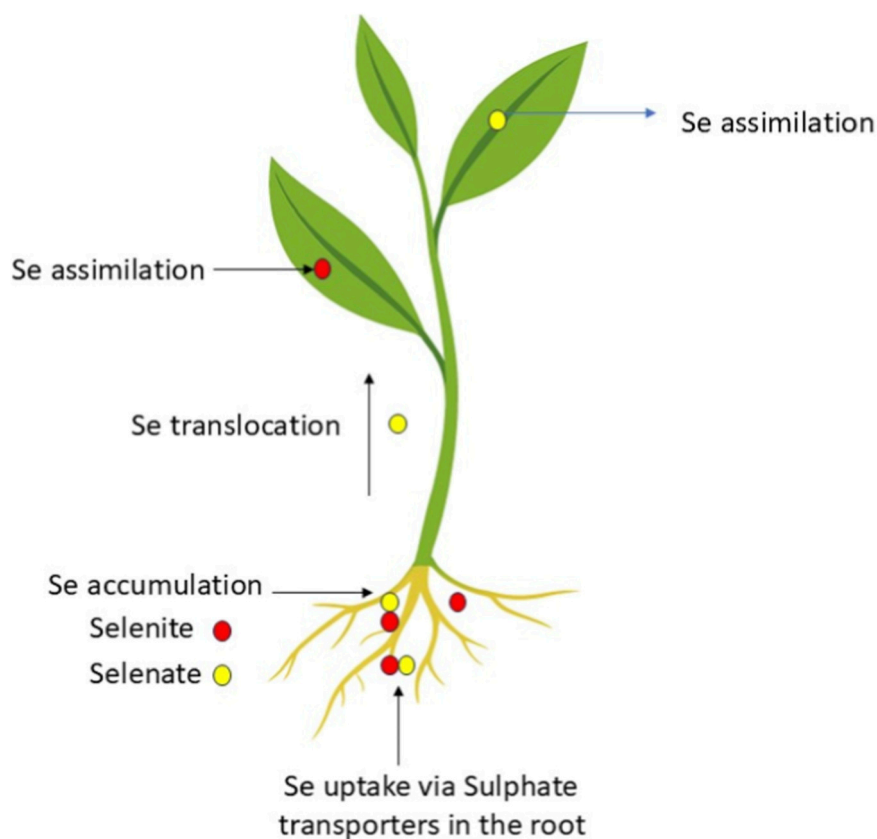


FIGURE 5

Schematic representation of selenium uptake and transport in plants: Selenium is absorbed by roots via sulphate transporter, then translocated, accumulated, and utilized in various plant tissues.

Following uptake, selenium is metabolized via sulfur assimilation pathways and incorporated into bioorganic forms (Figure 5), such as selenocysteine (SeCys) and selenomethionine (SeMet), which are subsequently utilized as building blocks to produce proteins (Chao et al., 2022; Zhou et al., 2021). Selenium hyperaccumulators, such as those in the genus *Astragalus*, have developed distinct mechanisms to tolerate and even accumulate large amounts of selenium, commonly through methylation processes, allowing for phytoremediation of selenium-laden soils (Hasanuzzaman et al., 2020a; He et al., 2024). Based on recent research, SeNPs may enter root tissues through endocytosis-like mechanisms or the apoplastic pathway, especially if the particle size is small enough (<50–100 nm) to enter through cell wall pores or be internalised by plasma membrane invagination (Dietz et al., 2011; Wang et al., 2020). Nanoparticle-like formations in root cortical cells and vascular tissues have occasionally been discovered by transmission electron microscopy and fluorescence-based tracking, suggesting potential intact transit (Li et al., 2020; Qi et al., 2021). However, there is still a lack of definitive visualisation of endocytosis-driven SeNP uptake, and it is still difficult to differentiate intact SeNPs from altered or aggregated selenium species within plant tissues. On the other hand, growing research suggests that dissolution-mediated absorption might be the primary route for acquiring selenium after SeNP treatment. SeNPs can partially oxidise or dissolve in soil-plant systems, releasing available selenium species like selenite or selenate

that are then absorbed by known sulphur or selenium transporters (Benjamin et al., 2012; Schiavon and Pilon-Smits, 2017). According to Wang et al. (2020) and Sarkar et al. (2023), a number of studies that demonstrate improved selenium accumulation and physiological benefits after SeNP treatment relate these effects mainly to altered selenium ions rather than intact nanoparticles.

3.2 Functional roles of selenium metabolites in plants

Se is commonly used in agriculture, either as a soil amendment or through foliar application, to enhance crop yield, reduce damage from environmental stress, and increase selenium compounds in plant parts (Pezzarossa et al., 2012). However, its application requires careful regulation because the margin between the hazardous and useful concentrations of Se is very limited. A deeper understanding of the roles and metabolic fates of different seleno compounds is essential for developing safe and precise biofortification strategies. Beyond the already recognized selenometabolites, several additional forms remain to be identified, and their nutritional values and toxicity levels remain incompletely understood.

One of the key ways in which selenium (Se) aids stress tolerance is by managing reactive oxygen species (ROS). Selenoamino acids

(SeMet) and (SeCys) can function directly as antioxidants or assist in the production of Se-dependent antioxidant enzymes. These enzymes include glutathione peroxidases (GPx), thioredoxin reductases, and methionine sulfoxide reductases, which are also involved in protein repair processes. The nucleophilic characteristics of selenol groups (RSe^-) and the ease with which SeMet and SeCys undergo oxidation enhance the antioxidant capabilities of these amino acids. The presence of SeCys at the catalytic sites, selenoenzymes generally exhibit higher catalytic activity against reactive oxidants than sulfur-containing analogues (Rahmanto and Davies, 2011). According to Chauhan et al. (2019), stimulation of antioxidant defence systems under Se supplementation was reported in several crops. Hartikainen et al. (2000) documented a rise in GPx activity in ryegrass treated with Se. Similar enhancements in GPx action were reported in plants that were affected by Cd (Filek et al., 2008), salinity (Hasanuzzaman and Fujita, 2011), drought (Hasanuzzaman and Fujita, 2011), and As Chauhan et al. (2017) stress. The result shows that GPx are the central action for counteracting the effects of oxidative stress. Moreover, Se treatment has been shown to boost the function of other antioxidant enzymes, including superoxide dismutase (SOD), ascorbate peroxidase (APX), catalase (CAT), and glutathione reductase (GR) (Feng et al., 2013; Kumar et al., 2014). The amount of ascorbate, tocopherol, and polyphenols are elevated in stressed plants upon Se supplementation, further aiding oxidative stress mitigation (Hasanuzzaman and Fujita, 2011).

Selenohomolanthionine (SeHLan), another significant selenium metabolite, has been extracted from plants such as Indian mustard (*Brassica juncea*), Japanese radish (*Raphanus sativus* L.), wheat (*T. aestivum*), and selenium-enhanced yeast (Duncan et al., 2017). SeHLan is regarded as a precursor to SeCys (Anan et al., 2011). Notably, it seems to be less harmful to mammals compared to SeMet, indicating its potential as a safer option for selenium biofortification initiatives (Anan et al., 2011). Plants primarily take up selenium as selenate through sulfate transporters and as selenite through phosphate transporters, with the former exhibiting higher mobility and being translocated to the shoots (Khan et al., 2019; Liang et al., 2019). Once absorbed, selenium undergoes metabolism through sulfur assimilation pathways and is then converted into bioorganic types (SeCys) and (SeMet), which are then used as fundamental components for protein synthesis (Chao et al., 2022; Zhou et al., 2021). Selenium hyperaccumulators, like those found in the *Astragalus* genus, have evolved unique strategies to endure and even gather substantial amounts of selenium, often through methylation processes, enabling the process of phytoremediation in selenium-affected soils (Hasanuzzaman et al., 2020a; He et al., 2024).

4 Selenium nanoparticles (SeNPs) in agriculture: synthesis and multifunctional role

Selenium nanoparticles (SeNPs) are becoming more popular with its exceptional biological actions (Figure 6). Unlike bulk selenium, which can be toxic at high concentrations, nano sized selenium exhibits reduced toxicity and higher bioavailability, making it promising for biomedical, food, and environmental

applications (Table 2). The synthesis method is essential in establishing the size, morphology, stability, and functional properties of SeNPs, which in turn influence their possible uses (Sampath et al., 2024; Andrés et al., 2025).

4.1 Methods of selenium nanoparticle synthesis

4.1.1 Chemical synthesis

Chemical synthesis is a widely employed method for SeNP production. Typically, selenium salts such as sodium selenite or selenous acid act as precursors and are reduced by chemical agents, including ascorbic acid, hydrazine, glutathione, or metallic reducing agents like titanium (III) chloride and iron (II). These methods are relatively fast and enable precise control over particle size, which often ranges between 40 and 100 nm. Kalaparthy et al. (2020) synthesized crystalline SeNPs by reducing sodium selenite with titanium (III) chloride under ambient conditions, producing nanoparticles of 40–90 nm with good stability. Similarly, Kurimella et al. (2013) demonstrated a simple wet chemical method using Fe(II) as a reducing agent, which produced SeNPs without the need for post-annealing (Kurimella et al., 2013). While chemical synthesis offers reproducibility and scalability, the use of toxic chemicals can limit biomedical applications unless purification steps are applied (Table 3; Figure 7).

4.1.2 Physical synthesis

These techniques include the application of high-energy, such as laser ablation, gamma irradiation, microwave irradiation, or ultrasonic treatment. These approaches provide highly pure nanoparticles since no additional stabilising agents are required, thereby reducing contamination risks. Laser ablation in liquids, for example, can generate SeNPs directly from bulk selenium, yielding uniform particles with controllable sizes. However, these methods require expensive instrumentation and high energy inputs, which may limit their cost-effectiveness for large-scale production. Despite this, they are valuable in applications demanding ultrapure SeNPs, such as electronics and nanomedicine (Zhang et al., 2023).

4.1.3 Green synthesis

Green synthesis has become a sustainable alternative to chemical and physical approaches. This method utilises biological systems like plants, bacteria, fungi, and yeasts, which reduce selenium oxyanions into nanoparticles. Plant-mediated synthesis is particularly appealing, as phytochemicals such as flavonoids, alkaloids, and polyphenols act simultaneously as capping and reducing agents. Perumal et al. (2021) produced SeNPs using *Enicostema axillare* leaf extract, producing particles between 56 and 98 nm that displayed significant antibacterial and anticancer activities (Perumal et al., 2021). Microbial systems offer another green route, where organisms such as *Bacillus subtilis* and *Saccharomyces cerevisiae* enzymatically reduce selenium compounds, leading to biocompatible SeNPs with high bioactivity (Sampath et al., 2024). Compared to chemical synthesis, green methods are cost-effective, eco-friendly, and safer, though particle uniformity may vary depending on the biological extracts used.

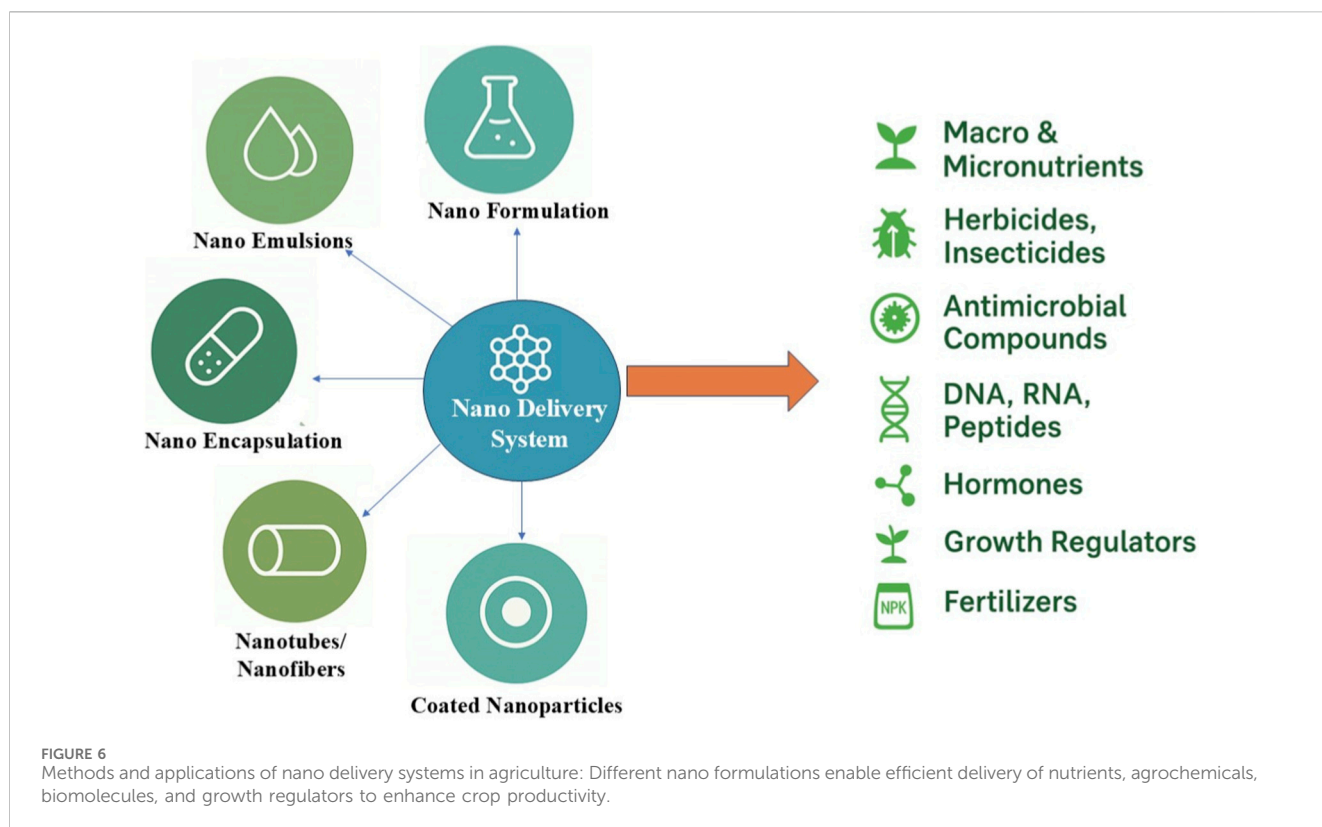


TABLE 2 A comparative analysis of selenium nanoparticles (SeNPs) and ionic selenium (selenate/selenite) in plants.

S.No	Aspect	Selenium nanoparticles (SeNPs)	Selenate/Selenite (SeO ₄ ²⁻ /SeO ₃ ²⁻)	References
1	Uptake mechanism	Size and surface dependent, potential apoplasmic transport or endocytosis	Transporter mediated uptake via sulfate/selenate transporters	Dietz et al., 2011; Zhang X. et al 2020; Winkel et al., 2015
2	Bioavailability	Controlled release, sustained availability	Rapid dissolution and assimilation	Sarkar et al., 2023; Kah et al., 2019
3	Toxicity profile	Lower acute toxicity due to controlled release and nano-scale behavior	Higher acute toxicity risk at high concentrations	Zhang P. et al 2020; Schiavon and Pilon-Smits, 2017
4	Surface reactivity	High; interacts with roots, cell walls, and rhizosphere micro organisms	Minimal surface interaction	Raliya et al., 2017; Dietz et al., 2011
5	Persistence in soil/plant system	Longer residence time, slow transformation	Rapid transformation and assimilation	Sarkar et al., 2023; Winkel et al., 2015
6	Antioxidant and physiological effects	Enhanced activity of SOD, CAT, GPX; improved stress tolerance; gradual nutrient supplementation	Similar antioxidant response via general selenium metabolism	Winkel et al., 2015; Schiavon and Pilon-Smits, 2017; Hasanuzzaman et al., 2020b
7	Heavy metal stress mitigation	Reduces metal uptake via complexation; protects against cd, pb, As, cr	Limited capacity	Yuan et al. (2024)

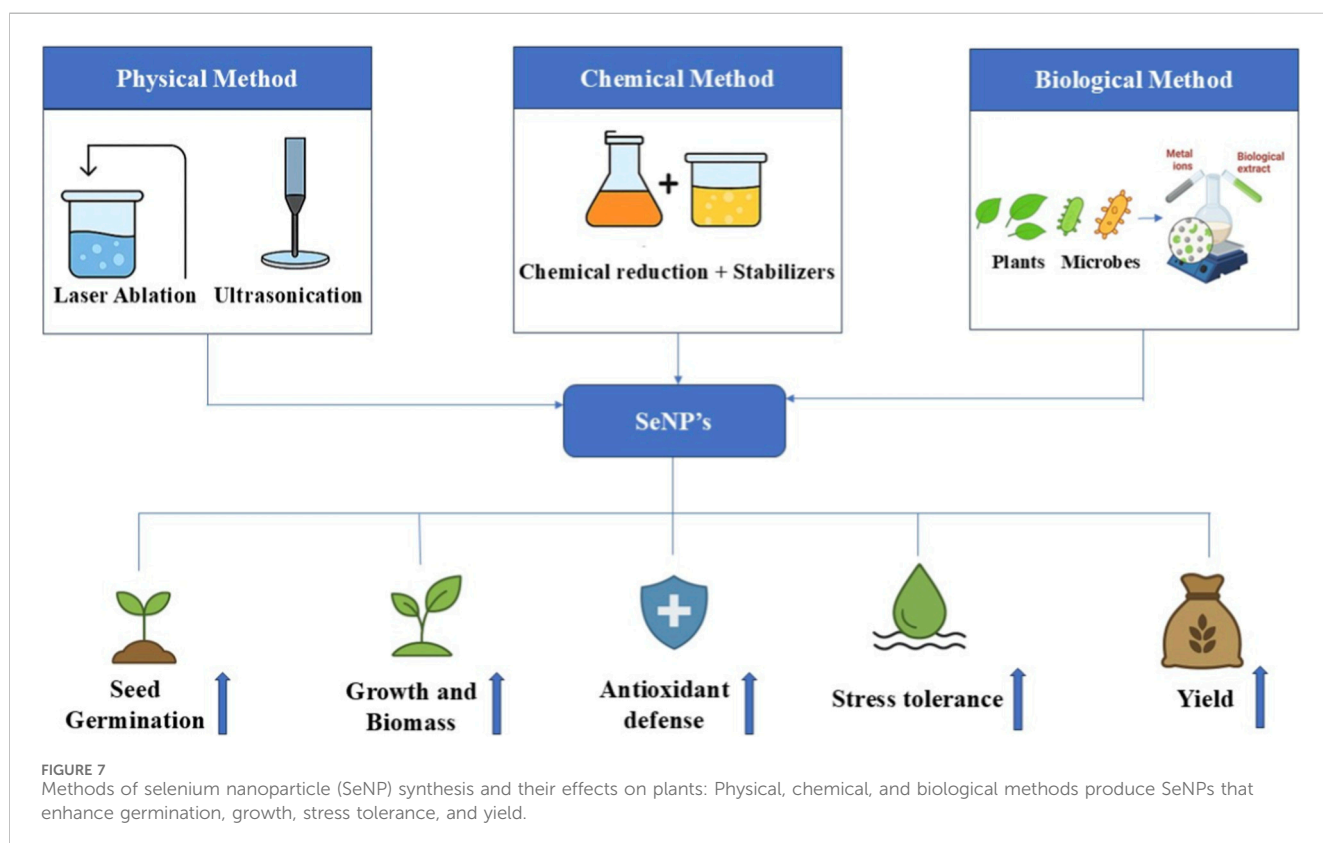
Recent studies suggest that chemical methods remain popular due to their simplicity and control, while physical methods excel in producing pure nanoparticles for advanced industrial applications. However, biological methods are gaining momentum for biomedical uses because they avoid toxic byproducts and yield nanoparticles with enhanced stability and biocompatibility. The trend in current research points toward green synthesis as the most promising strategy for future therapeutic and environmental applications of SeNPs (Zhang et al., 2023; Sampath et al., 2024).

4.2 Control of gene expression in crop plants

Selenium uptake in plants occurs mainly via transporters shared with sulfate and phosphate. After being absorbed, whether as selenate or selenite, it can be integrated into amino acids like selenocysteine and selenomethionine and then become part of structural or functional proteins. While this substitution can strengthen stress defence and metabolic activity, excessive

TABLE 3 Methods of selenium nanoparticle synthesis.

S.No	Method	Process	Advantages	Limitations	Example and reference
1	Chemical	Reduction of selenium salts (e.g., sodium selenite) using chemical agents (ascorbic acid, hydrazine, TiCl_3 , Fe^{2+})	Fast and reproducible, good size control (40–100 nm)	Use of toxic reagents, requires purification for biomedical use	SeNPs synthesized using Ti(III) chloride, yielding 40–90 nm stable particles (Kalaparathi et al., 2020)
2	Physical	High-energy input methods: Laser ablation, gamma irradiation, sonication, microwave irradiation	Produces ultrapure nanoparticles, No chemical contamination	Requires expensive instruments high energy consumption, limited scalability	Laser ablation used to synthesize uniform SeNPs for nanomedicine and electronics (Zhang et al., 2023)
3	Biological (plant-mediated)	Use of phytochemicals (flavonoids, alkaloids, phenolics) in plant extracts as capping and reducing agents	Economical and environmental friendly, produces biocompatible SeNPs, No toxic byproducts	Variability in particle size and shape due to complex plant metabolites	<i>Enicostema axillare</i> extract produced 56–98 nm SeNPs with antibacterial and anticancer effects (Perumal et al., 2021)
4	Biological (microbial-mediated)	Enzymatic reduction of selenium oxyanions by bacteria, fungi, or yeast	Produces highly stable and bioactive SeNPs, scalable and eco-friendly	Slower process than chemical methods, requires sterile conditions	Microbial systems such as <i>Bacillus subtilis</i> and <i>Saccharomyces cerevisiae</i> used for green SeNP synthesis (Sampath et al., 2024)



replacement may generate nonspecific or toxic proteins (Sarwar et al., 2020). Recent transcriptomic and metabolomic research findings provide knowledge of the molecular system by which SeNPs influence plant gene expression, secondary metabolism, and stress tolerance.

4.2.1 Cell wall reinforcement and lignin biosynthesis

Transcriptome profiling in cadmium selenide-treated plants revealed metabolic shifts linked to root cell wall stability. The

upregulation of lignin biosynthetic genes, such as PAL (phenylalanine ammonia-lyase), 4CL (4-coumarate-CoA ligase), CAD (cinnamyl alcohol dehydrogenase), and COMT (caffeic acid O-methyltransferase), was observed alongside an increase in phenylpropanoid derivatives like erisolin, phenylalanine, p-coumarin, cafestol, and coniferaldehyde (Li et al., 2021).

4.2.2 Hormonal regulation and stress signalling

Genes such as *BZR1* (brassinosteroid signalling regulator), *LOX3* (lipoxygenase 3), and *NCED1* (9-cis-epoxycarotenoid dioxygenase

TABLE 4 Effect of Se on the accumulation of secondary metabolites in plants (Zhou et al., 2024).

S. No	Plant species	Mode of Se application	Secondary metabolites affected	Overall changes compared to control	References
1	<i>Brassica oleracea</i> var. <i>capitata</i> L. (cabbage)	Soil application (Se yeast)	Total glucosinolates	Increased	Tian et al. (2016)
2	Broccoli sprouts (FL60, WX90, SL120)	Foliar spray with Na ₂ SeO ₄ and Na ₂ SeO ₃	Total glucosinolates	Increased in WX90 under Na ₂ SeO ₄ ; No significant change in FL60 and SL120	Gui et al. (2022)
3	<i>Brassica oleracea</i> L. var. <i>italica</i> (broccoli)	Soil application (Se yeast/Na ₂ SeO ₃)	Total glucosinolates	Increased	Zhao et al. (2023)
4	Chinese cabbage sprouts	Foliar application with ZnSO ₄ , Na ₂ SeO ₃ , or mixture	Total glucosinolates	Increased	Dall'Acqua et al. (2019)
5	Radish	Foliar application/hydroponics with Na ₂ SeO ₄	Total glucosinolates	Increased in leaves (5 mg/plant) and roots (20 mg/plant); decreased in leaves (40 μM)	Schiavon et al. (2016)
6	<i>Eruca sativa</i> mill. And <i>Diplotaxis tenuifolia</i>	Hydroponics with Na ₂ SeO ₄	Total glucosinolates	Decreased in <i>E. sativa</i>	Malik et al. (2011)
7	Tomato	Hydroponics/foliar Na ₂ SeO ₄	Chlorogenic acid	Increased in leaves; decreased in roots	Schiavon et al. (2013)
8	Radish	Hydroponics/foliar Na ₂ SeO ₄	4-O-caffeoylquinic acid, caffeic acid hexose 1, quinic acid derivatives, kaempferol, rutin	Increased	Schiavon et al. (2016)
9	Chickpea	Hydroponics with Na ₂ SeO ₃	Total phenolic compounds	Increased in leaves; decreased in roots	Serrano-Sandoval et al. (2022)
10	Purple-grained wheat (202w17 and Shannong 129)	Soil and foliar application of Se ⁴⁺ (Se-enriched fertilizer and nutrient solution)	Total anthocyanins	Increased in foliar treatment (greater in 202w17); No significant change in Shannong 129	Xia et al. (2020)
11	<i>Lycium chinense</i> L.	Nutrient solution with Na ₂ SeO ₃	Chlorogenic acid, rutin	Increased	D'Amato et al. (2018)
12	Soybean	Hydroponics with Na ₂ SeO ₃	Total phenolics, total flavonoids	Both increased; flavonoids showed early increase followed by decline	Huang et al. (2024)
13	<i>Ocimum basilicum</i> L. (basil)	Hydroponics/foliar Na ₂ SeO ₄	Hydroxycinnamic acids, phenolics, flavonoids, anthocyanins	Increased; increased; No significant change; increased	Skrypnik et al. (2019)
14	Purple lettuce	Hydroponics with Na ₂ SeO ₃	Anthocyanins	Increased	Liu et al. (2018)
15	Pepper	Soil application of SeNPs	Chlorogenic acid, caffeic acid, vanillic acid, p-hydroxybenzoic acid, sinapic acid, ferulic acid, apigenin, rutin, luteolin	Increased (in roots, leaves, and fruits, depending on compound)	Tang et al. (2022)

1) were strongly upregulated following SeNP treatment. This led to a rise in the brassinosteroids, jasmonic acid, and abscisic acid production, which in turn enhanced stress resistance and promoted growth.

4.2.3 Secondary metabolism and crop quality

The application of SeNP with a concentration of 5 mg/L in *Capsicum annuum*, which was cultivated in a cadmium-affected area, results show notable rise in the levels of capsaicinoids: capsaicin increased by 29.6%, nordihydrocapsaicin by 44.2%, and dihydrocapsaicin by 45.3%. These metabolic alterations were associated with the turning on of genes in the phenylpropanoid and routes for branched chain fatty acids, such as BCAT, Fat, AT3, HCT, and Kas (Li L. et al., 2022) (Table 4).

4.2.4 Volatile organic compounds (VOCs)

Elevated concentrations of amyl alcohol, linalool oxide, e-2-heptanal, 2-hexenal, ethyl crotonate, and 2-butanone were observed in SeNP-treated plants. These compounds contribute to crop aroma, flavour, and resistance to pathogens, highlighting SeNP-mediated improvements in both stress resilience and market quality.

5 Role of SeNPs on biotic stress

5.1 Pests

Insect pests cause biotic stress, significantly hindering global agricultural productivity by adversely affecting crop growth, yield, and quality through direct feeding, pathogen transmission, and

TABLE 5 The function of SeNPs against biotic stress.

S.No	Plant disease and biotic stress factors	The host plant's name	Concentrations of SeNPs applied	SeNPs-mediated plant responses to biotic challenges	References
1	Fusarium wilt <i>Fusariumoxysporum</i>	Pot marigold	0.5, 1.0, 1.7, and 0.25 mg/mL	Fungicidal activity against fungal infections	Lazcano-Ramírez et al. (2023)
2	Anthraxnose <i>Colletotrichumcapsica</i> Early blight <i>Alternariasolani</i>	Chili <i>Capsicum annuum</i> Tomato, <i>Solanumlycopersicum</i>	50 and 100 ppm	SeNPs showed the unique capacity to aggregate, bind, and prevent the growth of <i>P. infestans</i> zoospores	Joshi et al. (2019)
3	Downy mildew <i>Sclerosporagraminicola</i>	Pearl millet <i>Pennisetumglaucum</i>	150 and 250ppm	SeNPs prevented <i>Sclerospora graminicola</i> from growing, sporulating, and surviving as zoospores	Nandini et al. (2017)
4	Sclerotinia stem rot <i>Sclerotiniasclerotiorum</i>	Oilseed rape <i>Brassica napus</i>	2.5–20 mg L ⁻¹	SeNPs enhanced antioxidant enzyme activities and increased the expression of defense genes. increased the amino acids and energy metabolism of <i>S. sclerotiorum</i> -infected leaves	Li et al., 2023; Xu et al., 2020
5	Fusarium head blight (FHB) or scab <i>Fusariumculmorum</i>	Wheat <i>Triticumaestivum</i> L.	0.1 mg/mL	A marked decrease infungal growth resulted in less disease and elevated amounts of chlorophyll and total carotenoids	El-Saadony et al. (2021)
6	<i>Bacillus subtilis</i>	Ashwagandha <i>Withaniasomnifera</i>	20, 50, and 100 µM	SeNPs exhibited notable antioxidant activity and significant antibacterial properties	Garza-García et al., 2022; Alagesan and Venugopal 2019
7	Larvae <i>Spodopteralitura</i>	Peanut <i>Arachishypogaea</i>	0, 7.5, 15, 30, and 45 µg Se kg ⁻¹ (soil application) and 0, 5, 10, and 15 µmol L ⁻¹ (nutrient solution)	External application of SeNPs on peanutplants led to a decrease in plant infestation by the parasite.SeNPs showed larvicidal effects, leading to substantial larval death	Arunthirumeni et al. (2022)

triggering host defence mechanisms (Perilla-Henao and Casteel, 2016; Kumar et al., 2021). Rapid developments in nanotechnology have introduced selenium nanoparticles (SeNPs) as promising substitutes for synthetic pesticides. Shang et al. (2022) demonstrated that SeNPs were highly effective against *Bursaphelenchus xylophilus*, showing reduced cytotoxicity in MC3T3-E1 cells in contrast to traditional SeO₂. Likewise, Amin et al. (2021) showed that *Penicillium*-mediated SeNPs successfully eliminated cutworms and improved sunflower growth and carotenoid accumulation by 167.4% at 20 mg/L (Table 5).

Traditional pesticides, accelerate the evolution of pest resistance due to the selective pressure they impose (Cao and Wang, 2022). Thus, developing novel, eco-friendly alternatives is essential. In wheat, applying SeNPs through foliar spraying led to a reduction in *Sitobionavenae* populations by 36.4%, 26.2%, and 11.5% at concentrations of 5, 10, and 20 mg/L then control. Interestingly, Xin et al. (2025) emphasized that SeNPs not only reduce pest abundance but also enhance plant defence signalling by modulating secondary metabolite pathways, thereby improving the overall resilience of plants to herbivory. This discovery is in line with the results of Zhou et al. (2021), who observed that the combination of SeNPs and melatonin enhanced resistance to aphids through boosting the synthesis of organic volatile compounds and controlling phenylpropanoid and indole metabolism. In a similar

vein, SeNPs mediated by *Trichoderma* made *Spodoptera litura* larvae more likely to die at a concentration of 100 mg/L (Arunthirumeni et al., 2022).

As a whole, these findings show that SeNPs act as larvicides, antifeedants, and resistance inducers, thereby offering a sustainable strategy to mitigate the problem of pesticide resistance. Their multifaceted action, direct toxicity, antifeedant activity, and defence priming positions SeNPs as valuable potential options for future integrated pest management plans.

5.2 Plant pathogens

SeNPs have shown a vast array of antimicrobial properties (Lin et al., 2024; Huang et al., 2016), effectively targeting various phytopathogens through several ways. Joshi et al. (2019) discovered that SeNPs produced by *Trichoderma* had a notable impact on *Magnaporthe oryzae*, a parasite that causes rice blast disease and also prevented infections by *Colletotrichum capsici* and *Alternaria solani* in pepper and tomato leaves with 50–100 mg/L concentration. In the same way, Lazcano-Ramírez et al. (2023) created SeNPs with extracts of *Amaranthus glaucus*, *Calendula officinalis*, which demonstrated antifungal activity towards *Fusarium* spores and *Colletotrichum gloeosporioides* at

concentrations of ≥ 0.25 mg/mL. On a mechanistic level, SeNPs facilitate the synthesis of reactive oxygen species (ROS) like superoxide radicals, H_2O_2 , and hydroxyl radicals, leading to oxidative stress inside pathogen cells (Qi et al., 2021; Attia et al., 2024). The raised ROS levels interfere with essential biomolecules such as lipids, DNA, and proteins, which causes structural and functional harm and eventually leads to cells dying (Zhou et al., 2024). Xin et al. (2025) also emphasized that the accumulation of ROS induced by SeNPs not only harms pathogens but also initiates systemic resistance in host plants, thereby connecting direct antimicrobial effects with host immunity. Direct interactions with cellular membranes further compromise integrity by altering permeability and triggering leakage of intracellular contents (Lin et al., 2024; Huang et al., 2025). SeNPs also inhibit essential enzymes like cytochrome c oxidase and ATP synthase, suppressing respiration and ATP production (Qi et al., 2021).

Along with their straight toxic impact, SeNPs disrupt the cell walls, proteins, and nucleic acids (Zhou et al., 2024), induce DNA strand breaks, and destabilise RNA, thereby hindering protein synthesis. They also enhance host immune defences by upregulating pathogenesis-related genes (e.g., PR1, PR2, PR4) and activating defence enzymes like catalase and β -1,3-glucanase (Joshi et al., 2021; El-sharkawy et al., 2025; Kang et al., 2023). SeNPs have been demonstrated to inhibit bacterial adhesion and biofilm formation (Serov et al., 2023) and to stimulate the secondary metabolites (Shahbaz et al., 2023; Ikram et al., 2024). Taken together, these studies highlight SeNPs as potent antimicrobial agents that operate through oxidative stress induction, enzymatic inhibition, membrane disruption, and immune priming. Their dual action direct inhibition of pathogens and stimulation of plant defences makes them a promising green nanotechnology for managing plant diseases.

6 Role of SeNPs on abiotic stress

6.1 Cold stress

Cold environments interfere with both physiological and metabolic processes in crops, hindering their growth and reducing their overall productivity (Liu et al., 2021). Current research shows that selenium nanoparticles (SeNPs) can mitigate cold-induced injury by enhancing the antioxidant machinery, stabilising membranes, and supporting osmotic regulation (Xin et al., 2025). Exposure to cold stress often results in a rise in reactive oxygen species (ROS), which can harm proteins, nucleic acids and lipids. SeNPs, through their high radical-scavenging potential, limit ROS accumulation and protect cellular integrity. One significant impact of cold stress is the suppression of photosynthesis. SeNPs help counter this decline by increasing chlorophyll concentration and stimulating enzymes associated with the photosynthetic pathway. In the case of peppers, the simultaneous use of SeNPs, zinc oxide, and *arbuscular mycorrhizal* fungi caused a rise in chlorophyll levels, photosynthesis rate, and yield when exposed to cold stress (Sayed et al., 2024). Similarly, applying Se to the leaves was found to boost photosynthesis and safeguard basil's growth under low-temperature conditions (Ramezan et al., 2024).

6.2 Heat stress

Rising global temperatures impose heat stress that triggers multiple injuries in plants, including protein denaturation (Ezquer et al., 2020), reduced enzyme function (Suseela et al., 2014), membrane oxidation, and disruption of primary metabolism (Dos Santos et al., 2024). Together, these effects hinder plant development and yield. Research shows that SeNPs can substantially reduce heat-associated damage by maintaining biomass accumulation (Liu et al., 2022), improving water metabolism and physiological balance (Omar et al., 2023), and reinforcing antioxidant defences (Soliman et al., 2023). In cucumber, the use of SeNP under conditions of combined salinity and heat stress enhanced both crop development and production (Shalaby et al., 2021). In wheat, foliar SeNP treatment (10 mg L^{-1}) improved photosynthesis, water-use efficiency, and membrane stability under simultaneous heat and drought stress, thereby enhancing crop resilience (Omar et al., 2023).

6.3 Water deficit stress

Water scarcity causes severe oxidative damage and growth inhibition in plants. SeNPs are known to strengthen drought tolerance by promoting root development, enhancing water uptake, and maintaining cellular hydration (Zeeshan et al., 2024). The application of 30 mg L^{-1} selenium nanoparticles (SeNPs) in wheat has been shown to significantly enhance shoot and root biomass, as well as increase leaf area and number (Ikram et al., 2024). In addition to these morphological advantages, SeNPs have been found to activate the antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX), thereby mitigating oxidative stress (Omar et al., 2023; Zeeshan et al., 2024). As seed priming agents, SeNPs improve germination and drought resistance; for instance, in tomato, SeNP priming enhanced antioxidant activity and supported growth under water deficit (Ishtiaq et al., 2023). SeNPs enhance photosynthesis (Asghari et al., 2023), regulate abscisic acid (ABA), and promote osmolyte accumulation (e.g., proline, sugars, sugar alcohols) to sustain osmotic balance (Nasiri et al., 2025). At the genetic level, they upregulate drought-responsive transcription factors, including members of the DREB, NAC, and WRKY families, which further reinforce tolerance (Singhal et al., 2023).

6.4 Salinity stress

Soil salinity continues as an important obstacle to the cultivation of crops, mainly because it affects water availability and disrupts ionic balance, particularly concerning sodium (Na^+) and potassium (K^+) equilibrium (de Almeida et al., 2022; Hao et al., 2021). SeNPs help mitigate the damage caused by salinity by adjusting ion transporters like Na^+/H^+ exchangers (NHX) and K^+ channel proteins (AKT1), which leads to decreased Na^+ accumulation and enhanced K^+ absorption (Rady et al., 2021). Salt stress also provokes ROS accumulation and membrane lipid peroxidation, leading to cell injury. SeNPs help neutralise these effects by enhancing antioxidant defences, as shown in wheat, bitter melon, and beans (Rady et al.,

2021; Zafar et al., 2024; Sheikhalipour et al., 2021). They also stimulate the synthesis of suitable substances, including proline, betaine, and soluble sugars, which maintain osmotic stability under saline conditions (Rady et al., 2021). The way in which proline biosynthesis genes (P5CS) and salt-adaptive transcriptive element from the MYB and AP2/ERF families are also upregulated following SeNP exposure, strengthening molecular adaptation mechanisms (Li D. et al., 2022; Nedjimi, 2025).

6.5 Toxic metal stress

Crop productivity and food safety are seriously threatened by the presence of hazardous heavy metals like cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), and chromium (Cr) in soil and water caused by mining operations, excessive agrochemical use, industrial effluents, and natural geochemical processes. These metals cause oxidative stress, hinder photosynthetic efficiency, interfere with nutrient uptake, and eventually limit growth and yield (DalCorso et al., 2013; Zhang et al., 2020; Rashid et al., 2024; Yuan et al., 2024). Selenium nanoparticles (SeNPs) significantly reduce metal-specific toxicity through coordinated physiological, biochemical, and molecular pathways, according to recent studies. In *Brassica chinensis* and pak choi, SeNP treatment dramatically decreased Cd absorption and translocation during cadmium stress while maintaining root activity and chlorophyll content (Zhu et al., 2022; Di et al., 2024). Similarly, by maintaining cellular redox balance and reducing metal-induced membrane damage, SeNPs have been demonstrated to reduce the toxicity of arsenic and chromium (Qi et al., 2021; Yuan et al., 2024). SeNPs reduce reactive oxygen species produced under Cd, Pb, and Hg stress at the biochemical level by increasing the activity of antioxidant enzymes such as glutathione peroxidase (GPX), catalase (CAT), and superoxide dismutase (SOD) (Albqmi et al., 2023; Xin et al., 2025). SeNPs facilitate intracellular binding and compartmentalisation of harmful metals like Cd and Pb by upregulating genes involved in metal detoxification and sequestration, such as metallothioneins (MTs) and phytochelatin synthases (PCS) (Li et al., 2020; Qi et al., 2021).

Furthermore, by creating stable Se metal complexes, SeNPs can directly lower metal bioavailability, which limits root absorption and long-distance transport of Cd and Cr inside plant tissues (Yuan et al., 2024). For example, SeNP supplementation improved the uptake of vital micronutrients including Fe, Mn, and Zn, which are necessary for recovering metabolic functioning under metal stress, while also reducing cadmium buildup in pak choi by up to 42%, according to Di et al. (2024). All of these results support the significance of SeNPs in reducing heavy metal stress in contaminated agroecosystems by showing a range of ways in which they improve plant tolerance to particular harmful metals (Table 6).

7 Challenges and constraints for field-level application of selenium nanoparticles

Despite the fact that selenium nanoparticles (SeNPs) have shown great promise in improving plant growth, stress tolerance,

and biofortification, the majority of research to date has been restricted to controlled laboratory or pot tests, which do not accurately reflect the variety of field settings. The stability and aggregation of nanoparticles caused by soil heterogeneity, moisture fluctuations, pH, ionic strength, organic matter, and microbial activity are just a few of the difficulties that field application faces. These factors can all lower the bioavailability and efficacy of SeNP (Kah et al., 2019; Sarkar et al., 2023). As dispersion and persistence can be impacted by variables like rainfall, irrigation, wind, and repeated application, delivery tactics including seed priming, soil integration, and foliar treatment are challenging to apply consistently at scale. Since the narrow margin between deficiency and toxicity, excessive or repetitive use may result in selenium buildup in soils and edible tissues, suggesting problems to food safety (Winkel et al., 2015; Schiavon and Pilon-Smits, 2017). Field adoption is further complicated by ecological and economic factors. While the possibility of trophic transfer and biomagnification is still mostly unknown, SeNPs may interact with non-target organisms, such as beneficial soil microbes and invertebrates, potentially causing oxidative stress and upsetting ecosystem functions (Hasanuzzaman et al., 2020b; Sarkar et al., 2023). Economically, unless scalable and economical green synthesis techniques are optimised, the high cost of nanoparticle synthesis, storage, and large-scale application restricts practical deployment (Raliya et al., 2017; Kah et al., 2019). Another challenge is the lack of standardised rules for risk assessment, labelling, and allowable application rates of nano-enabled fertilisers, as well as the current frameworks' inability to distinguish between bulk and nano-selenium. Therefore, multi-location studies, thorough life-cycle and cost-benefit evaluations, and the development of precise regulatory requirements to guarantee agronomic efficacy, environmental safety, and food security will be necessary for successful field-scale adoption.

8 Environmental and food safety concerns of selenium nanoparticles

The long-term environmental behaviour of selenium nanoparticles (SeNPs) is still unclear, despite the fact that they are frequently thought to be safer than bulk or ionic selenium forms. Selenium speciation and residence time may be changed by nanoparticle persistence in soil systems, raising the possibility of progressive accumulation with repeated applications (Sarkar et al., 2023). Because selenium has a small margin between nutritional necessity and toxicity, such persistence raises concerns about selenium accumulation in edible plant tissues, where excessive accumulation could exceed safe dietary limits (Winkel et al., 2015; Schiavon and Pilon-Smits, 2017). Additionally, new ecotoxicological data suggests that SeNPs may cause non-target toxicity to aquatic species, invertebrates, and beneficial soil microbes, possibly through membrane contacts and oxidative stress induction (Hasanuzzaman et al., 2022; Sarkar et al., 2023). Before large-scale agricultural deployment of SeNPs, thorough life-cycle and risk assessment studies are essential due to the potential for food-chain transfer and biomagnification, especially in agro-aquatic interfaces.

TABLE 6 Application of Se in biotic and abiotic stresses (Zhou et al., 2024).

S. No	Plant species	Form of Se application	Concentrations of SeNPs applied	Observed effect	References
1	<i>Saccharum</i> spp. hybrids (Sugarcane)	Nano-selenium	5 mg L ⁻¹ and 10 mg L ⁻¹ foliar spray	Enhanced antioxidant and jasmonic acid levels; lowered ROS accumulation under <i>Xanthomonas albilineans</i> infection, contributing to improved crop quality	Shi et al., 2023
2	<i>Phaseolus vulgaris</i> L. (common bean)	Combined nano-selenium and nano-silicon	100 ppm	Synergistic suppression of plant pathogen activity	Taha et al., 2023
3	<i>Oryza sativa</i> L. (rice)	Selenium bio-nanocomposite	20 units	Reduced cadmium uptake and alleviated cadmium-induced oxidative stress	Ran et al., 2024
4	<i>Gossypium hirsutum</i> L. (cotton)	Foliar selenium application	50, 100, 150 mg Se L ⁻¹	Decreased oxidative injury by reducing ROS accumulation under heat stress	Saleem et al., 2021
5	Bitter melon (<i>Momordica charantia</i>)	Chitosan-selenium nanoparticles	10 mg L ⁻¹ and 20 mg L ⁻¹ foliar spray	Mitigated oxidative stress through improved antioxidant enzyme activity	Sheikhhalipour et al. (2021)
6	<i>Glycine max</i> (soybean)	Na ₂ SeO ₄ and H ₃ BO ₃ (combined)	50 μM Na ₂ SeO ₄ and 1 mM H ₃ BO ₃	Strengthened antioxidant defense and reduced salt stress-induced oxidative damage	Rahman et al., 2021

9 Future directions

Despite the encouraging outcomes, most studies remain limited to controlled conditions, and further evidence from long-term field trials is needed. The interaction of SeNPs with soil microbiota and their environmental persistence is vital to ensure safe and sustainable application. With coordinated efforts integrating nanotechnology, plant physiology, and agronomy, SeNPs can be developed into practical tools to improve crop resilience, enhance nutritional quality, and secure agricultural productivity in light of a changing environment and rising global food needs. SeNPs are known to enhance antioxidant enzyme activity, ROS scavenging, and osmolyte accumulation in the treated generation mechanisms that are often linked to stress priming and epigenetic regulation in plants (e.g., DNA methylation and small RNA pathways). While direct studies on transgenerational effects of selenium nanoparticles (SeNPs) in plants are lacking, several lines of evidence from nanoparticle biology and plant epigenetics suggest plausible heritable outcomes. The research by Jiang et al. (2025) provides molecular, transcriptomic, and physiological evidence that Se strongly modulates antioxidant metabolism and gene regulation, which underlies the biological plausibility of heritable effects. Supporting the idea that Se-induced metabolic reprogramming might persist epigenetically. Yet, long-term multi-generational studies are required to determine whether SeNP-triggered tolerance is stably inherited or gradually attenuated through subsequent generations.

10 Conclusion

Selenium nanoparticles (SeNPs) represent a promising approach in sustainable agriculture with the potential to improve plant growth, production, and resistance under a variety of environmental conditions. Their distinct physicochemical characteristics set them apart from traditional

inorganic forms of selenium, allowing for enhanced nutritional efficiency, targeted delivery, and lower risks of toxicity. Recent research shows that by preserving membrane stability, improving photosynthetic efficiency, regulating osmolyte accumulation, and reprogramming important metabolic and hormonal processes, SeNPs reduce abiotic stressors such as drought, salinity, and heavy metal toxicity. Furthermore, by functioning as antibacterial and antifungal agents and simultaneously inducing host defence responses through the activation of defense-related proteins and phenolic chemicals, SeNPs provide protection against biotic stressors. Despite these developments, there are still significant gaps in our understanding of the precise physiological, molecular, and dose-dependent mechanisms driving interactions between SeNP and plants. Comparative analyses across crop species and stress types, application dose optimisation to optimise benefits while minimising potential toxicity, and integrative molecular studies utilising proteomics, metabolomics, and genomics to clarify signalling networks governing SeNP-mediated stress tolerance should be the top priorities for future research. The safe, efficient, and widespread application of SeNPs in contemporary agriculture which will ultimately assist sustainable crop production and food security in the face of global environmental challenges will depend on filling these gaps.

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References

- Alagesan, V., and Venugopal, S. (2019). Green synthesis of selenium nanoparticle using leaves extract of *withaniasomnifera* and its biological applications and photocatalytic activities. *BioNanoScience* 9, 105–116. doi:10.1007/s12668-018-0566-8
- Albqmi, M., Yaghoubi Khanghahi, M., Selim, S., Al-Sanea, M. M., Alnusaire, T. S., Almuhayawi, M. S., et al. (2023). Positive interaction of selenium nanoparticles and olive solid waste on vanadium-stressed soybean plant. *Agriculture* 13 (2), 426. doi:10.3390/agriculture13020426
- Amin, M. A., Ismail, M. A., Badawy, A. A., Awad, M. A., Hamza, M. F., Awad, M. F., et al. (2021). The potency of fungal-fabricated selenium nanoparticles to improve the growth performance of *Helianthus annuus* L. and control of cutworm *agrotisipsilon*. *Catalysis* 11 (12), 1551. doi:10.3390/catal11121551
- Anan, Y., Mikami, T., Tsuji, Y., and Ogra, Y. (2011). Distribution and metabolism of selenohomolanthionine labeled with a stable isotope. *Anal. Bioanalytical Chemistry* 399 (5), 1765–1772. doi:10.1007/s00216-010-4143-4
- Andrés, C. M. C., Pérez de la Lastra, J. M., Munguira, E. B., Juan, C. A., and Pérez-Lebeña, E. (2025). Selenium nanoparticles in critical illness—anti-inflammatory and antioxidant effects. *Dietetics* 4 (1), 6.
- Arunthirumeni, M., Veeramal, V., and Shivakumar, M. S. (2022). Biocontrol efficacy of mycosynthesized selenium nanoparticle using *tricho Derma* sp. on insect Pest *Spodoptera litura*. *J. Clust. Sci.* 33, 1645–1653. doi:10.1007/s10876-021-02095-4
- Asghari, J., Mahdavi, H., Rezaei-Chiyaneh, E., Banaei-Asl, F., Amani Machiani, M., and Harrison, M. T. (2023). Selenium nanoparticles improve physiological and phytochemical properties of basil (*Ocimum basilicum* L.) under drought stress conditions. *Land* 12 (1), 164. doi:10.3390/land12010164
- Attia, M. S., Salem, S. S., Elakraa, A. A., Abdel-Maksoud, M. A., Malik, A., Kiani, B. H., et al. (2024). Promising antagonistic effect of bimetallic silver-selenium nanoparticles against *Ralstonia solanacearum*-causing wilt disease in eggplant (*Solanum melongena* L.). *Physiol. Mol. Plant Pathol.* 133, 102369.
- Benbrook, C., Kegley, S., and Baker, B. (2021). Organic farming lessens reliance on pesticides
- Benjamin, L. W., Enrico, S., and William, Z. (2012). Protein targeting to subcellular organelles via mRNA localization. *Biochim. etBiophysica Acta (BBA) - General Subj.* 1833 (2), 260–273. doi:10.1016/j.bbamcr.2012.04.004
- Bodnar, M., Konieczka, P., and Namiesnik, J. (2012). The properties, functions, and use of selenium compounds in living organisms. *J. Environ. Sci. Health, Part C* 30 (3), 225–252. doi:10.1080/10590501.2012.705164
- Cao, X., and Wang, Z. (2022). Application of nano-agricultural technology for biotic stress management: mechanisms, optimization, and future perspectives. *Environ. Sci. Nano* 9 (12), 4336–4353. doi:10.1039/D2EN00663B
- Chao, W., Rao, S., Chen, Q., Zhang, W., Liao, Y., Ye, J., et al. (2022). Advances in research on the involvement of selenium in regulating plant ecosystems. *Plants* 11 (20), 2712. doi:10.3390/plants11202712
- Chauhan, R., Awasthi, S., Tripathi, P., Mishra, S., Dwivedi, S., Niranjana, A., et al. (2017). Selenite modulates the uptake and toxicity of arsenic in rice (*Oryza sativa* L.). *Ecotoxicol. Environ. Saf.* 138, 47–54. doi:10.1016/j.ecoenv.2016.12.013
- Chauhan, R., Awasthi, S., Srivastava, S., Dwivedi, S., Pilon-Smits, E. A., Dhankher, O. P., et al. (2019). Understanding selenium metabolism in plants and its role as a beneficial element. *Crit. Rev. Environ. Sci. Technol.* 49 (21), 1937–1958. doi:10.1080/10643389.2019.1598240
- DalCorso, G., Fasani, E., Manara, A., Visioli, G., and Furini, A. (2013). Heavy metal pollution: state of the art and innovation in phytoremediation. *Int. J. Mol. Sci.* 14 (7), 14021–14069. doi:10.3390/ijms140714021
- Dall'Acqua, S., Ertani, A., Pilon-Smits, E. A. H., Fabrega-Prats, M., and Schiavon, M. (2019). Selenium biofortification differentially affects sulfur metabolism and accumulation of phytochemicals in two rocket species (*Eruca sativa* Mill. And *Diplotaxis tenuifolia*) grown in hydroponics. *Plants* 8 (3), 68. doi:10.3390/plants8030068
- de Almeida, H. J., Carmona, V. V., Dutra, A. F., and Cecílio Filho, A. B. (2022). Growth and physiological responses of cabbage cultivars biofortified with inorganic selenium fertilizers. *Sci. Hortic.* 302, 111154. doi:10.1016/j.scienta.2022.111154
- Di, X., Jing, R., Xie, S., Sun, Y., and Huang, Q. (2024). Biofortification of bok choy with selenium nanoparticles and its inhibitory effects on cadmium accumulation. *Plant Soil* 494 (1), 701–716. doi:10.1007/s11104-023-06318-7
- Dietz, K. J., and Herth, S. (2011). Plant nanotoxicology. *Trends Plant Science* 16 (11), 582–589. doi:10.1016/j.tplants.2011.08.003
- dos Santos, L. C., Martins, G. S., de Sousa Lima, J., da Silva, G. A. M., Nunes, M. F. P. N., de Oliveira, I. P., et al. (2024). Enhancing wheat resilience to water deficit through selenium biofortification: perspectives on physiological, biochemical and nutritional responses. *J. Soil Sci. Plant Nutr.* 24 (4), 7418–7435. doi:10.1007/s42729-024-02049-5
- Duncan, E. G., Maher, W. A., Jagtap, R., Krikowa, F., Roper, M. M., and O'Sullivan, C. A. (2017). Selenium speciation in wheat grain varies in the presence of nitrogen and sulphur fertilisers. *Environ. Geochem. Health* 39 (4), 955–966. doi:10.1007/s10653-016-9857-6
- D'Amato, R., De Feudis, M., Hasuoka, P. E., Regni, L., Pacheco, P. H., Onofri, A., et al. (2018). The selenium supplementation influences olive tree production and oil stability against oxidation and can alleviate the water deficiency effects. *Front. Plant Sci.* 9, 1191. doi:10.3389/fpls.2018.01191
- El-Saadony, M. T., Saad, A. M., Najjar, A. A., Alzahrani, S. O., Alkhatib, F. M., Shafi, M. E., et al. (2021). The use of biological selenium nanoparticles to suppress *Triticumaestivum*. *Saudi J. Biol. Sci.* 28, 4461–4471. doi:10.1016/j.sjbs.2021.04.043
- El-Sharkawy, H. H., Mostafa, N. A., Yousef, S. A., El-Blasy, S. A., and Badeea, O. A. E. (2025). Enhancing trichoderma efficacy in managing wheat stem rust disease and boosting production through the application of certain chemical inducers. *BMC Plant Biol.* 25 (1), 562. doi:10.1186/s12870-025-06434-9
- Ezquer, I., Salinas, P., Carneros, E., and Pineiro, M. (2020). Plant responses to heat stress: from molecular mechanisms to biotechnological applications. *J. Exp. Bot.* 71 (15), 4678–4691. doi:10.1093/jxb/eraa238
- Feng, R., Wei, C., and Tu, S. (2013). The roles of selenium in protecting plants against abiotic stresses. *Environ. Exp. Bot.* 87, 58–68. doi:10.1016/j.envexpbot.2012.09.002
- Filek, M., Keskinen, R., Hartikainen, H., Szarejko, I., Janiak, A., Miszalski, Z., et al. (2008). The protective role of selenium in rape seedlings subjected to cadmium stress. *J. Plant Physiology* 165 (8), 833–844. doi:10.1016/j.jplph.2007.06.006
- Fox, P., Leduc, D., Hussein, H., Lin, Z., and Terry, N. (2002). Selenium speciation in soils and plants. *ACS Symp. Ser.* 835, 339–354.
- Freeman, J. L., Tamaoki, M., Stushnoff, C., Quinn, C. F., Cappa, J. J., Devonshire, J., et al. (2007). Molecular mechanisms of selenium tolerance and hyperaccumulation in *Stanleya pinnata*. *Plant Physiol.* 144 (3), 1233–1244. doi:10.1104/pp.107.096032
- Garza-García, J. J. O., Hernández-Díaz, J. A., Zamudio-Ojeda, A., León Morales, J. M., Guerrero-Guzmán, A., Sánchez-Chiprés, D. R., et al. (2022). The role of selenium nanoparticles in agriculture and food technology. *Biol. Trace Elem. Res.* 200 (5), 2528–2548. doi:10.1007/s12011-021-02847-3
- Goulson, D. (2014). Pesticides linked to bird declines. *Nature* 511 (7509), 295–296. doi:10.1038/nature13642

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- Gui, J., Rao, S., Gou, Y., Xu, F., and Cheng, S. (2022). Comparative study of the effects of selenium yeast and sodium selenite on selenium content and nutrient quality in broccoli florets (*Brassica oleracea* L. Var. *italica*). *J. Sci. Food Agric.* 102 (4), 1707–1718. doi:10.1002/jsfa.11518
- Gupta, M., and Gupta, S. (2016). An overview of selenium uptake, metabolism, and toxicity in plants. *Front. Plant Sci.* 7, 2074. doi:10.3389/fpls.2016.02074
- Hao, H., Zhang, N., Wang, X., Li, S., and Yang, J. (2021). Soil salinization and its impact on crop production in coastal areas: a review. *Agronomy* 11 (6), 1189. doi:10.3390/agronomy11061189
- Hartikainen, H., Xue, T., and Piironen, V. (2000). Selenium as an antioxidant and pro-oxidant in ryegrass seedlings. *Plant Soil* 225 (1–2), 193–200. doi:10.1023/A:1026512921026
- Hasanuzzaman, M., and Fujita, M. (2011). Selenium pretreatment upregulates the antioxidant defense and Methylglyoxal detoxification system and confers enhanced tolerance to drought stress in rapeseed seedlings. *Biol. Trace Elem. Res.* 143 (3), 1758–1776. doi:10.1007/s12011-011-8998-9
- Hasanuzzaman, M., Bhuyan, M. B., Raza, A., Hawrylak-Nowak, B., Matraszek-Gawron, R., Nahar, K., et al. (2020a). Selenium toxicity in plants and environment: biogeochemistry and remediation possibilities. *Plants* 9 (12), 1711. doi:10.3390/plants9121711
- Hasanuzzaman, M., Bhuyan, M. B., Zulfikar, F., Raza, A., Mohsin, S. M., Mahmud, J. A., et al. (2020b). Reactive oxygen species and antioxidant defense in plants under abiotic stress: revisiting the crucial role of a universal defense regulator. *Antioxidants* 9 (8), 681. doi:10.3390/antiox9080681
- Hasanuzzaman, M., Nahar, K., García-Caparrós, P., Parvin, K., Zulfikar, F., Ahmed, N., et al. (2022). Selenium supplementation and crop plant tolerance to metal/metalloid toxicity. *Front. Plant Sci.* 12, 792770. doi:10.3389/fpls.2021.792770
- He, S. X., Liu, Y. W., Zhou, Q. Y., Liu, C. J., Li, W., and Ma, L. Q. (2024). Selenium increases antimony uptake in *As-hyperaccumulator* *Pteris vittata* and *Pteris cretica* by promoting antimonate reduction: GSH-GSSG cycle and arsenate reductases HAC1/ACR2. *J. Hazard. Mater.* 480, 135875. doi:10.1016/j.jhazmat.2024.135875
- Huang, C., Quan, X., Yin, Y., Ding, X., Yang, Z., Zhu, J., et al. (2024). Enrichment of flavonoids in short-germinated Black soybeans (*Glycine max* L.) induced by slight acid treatment. *Foods* 13 (6), 868. doi:10.3390/foods13060868
- Huang, S., Han, Y., Song, R., Wang, X., Zhou, Y., Luo, H., et al. (2025). Effects of bio-nano-selenium on wheat grain morphology, selenium transport enrichment and antioxidant enzyme activities. *Front. Plant Sci.* 16, 1516005. doi:10.3389/fpls.2025.1516005
- Huang, J. Q., Ren, F. Z., Jiang, Y. Y., and Lei, X. (2016). Characterization of selenoprotein M and its response to selenium deficiency in chicken brain. *Biol. Trace Elem. Res.* 170 (2), 449–458.
- Hussein, H. A. A., Darwesh, O. M., Mekki, B. B., and El-Hallouty, S. M. (2019). Evaluation of cytotoxicity, biochemical profile and yield components of groundnut plants treated with nano-selenium. *Biotechnol. Rep.* 24, e00377. doi:10.1016/j.btre.2019.e00377
- Ikram, M., Raja, N. I., Mohamed, A. H., Mashwani, Z. U. R., Omar, A. A., Gharibi, H., et al. (2024). Differential impact of plant-based selenium nanoparticles on physio-biochemical properties, antioxidant defense system and protein regulation in fruits of huanglongbing-infected 'kinnow' mandarin plants. *Front. Plant Sci.* 15, 1476497. doi:10.3389/fpls.2024.1476497
- Ishtiaq, M., Mazhar, M. W., Maqbool, M., Hussain, T., Hussain, S. A., Casini, R., et al. (2023). Seed priming with the selenium nanoparticles maintains the redox status in the water stressed tomato plants by modulating the antioxidant defense enzymes. *Plants* 12 (7), 1556. doi:10.3390/plants12071556
- Jiang, X., Yu, H., Yin, J., Ullah, F., Zhang, X., Chen, D., et al. (2025). Transcriptome analysis of the effects of selenium form and concentration on rice growth and metabolism at the seedling stage. *Agronomy* 15 (4), 867. doi:10.3390/agronomy15040867
- Joshi, S., De Britto, S., Jogaiah, S., and Ito, S. (2019). Mycogenic selenium nanoparticles as potential new generation broad spectrum anti fungal molecules. *Biomolecules* 9, 419. doi:10.3390/biom9090419
- Joshi, S. M., De Britto, S., and Jogaiah, S. (2021). Myco-engineered selenium nanoparticles elicit resistance against tomato late blight disease by regulating differential expression of cellular, biochemical and defense responsive genes. *J. Biotechnol.* 325, 196–206. doi:10.1016/j.jbiotec.2020.10.023
- Kah, M., Kookana, R. S., Gogos, A., and Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nat. Nanotechnology* 13 (8), 677–684. doi:10.1038/s41565-018-0131-1
- Kah, M., Tufenkji, N., and White, J. C. (2019). Nano-enabled strategies to enhance crop nutrition and protection. *Nat. Nanotechnology* 14 (6), 532–540. doi:10.1038/s41565-019-0439-5
- Kalaparthy, R., Korapu, S., Gandam, H., and Kurimella, V. R. (2020). Synthesis of selenium nanoparticles using sodium selenite [Se(IV)] as A precursor and Titanium(III) chloride as A reducing agent. *Int. J. Eng. Res. Technol.* doi:10.17577/IJERTV9IS040384
- Kang, L., Wu, Y., Jia, Y., Chen, Z., Kang, D., Zhang, L., et al. (2023). Nano-selenium enhances melon resistance to *Podosphaera xanthii* by enhancing the antioxidant capacity and promoting alterations in the polyamine, phenylpropanoid and hormone signaling pathways. *J. Nanobiotechnology* 21 (1), 377. doi:10.1186/s12951-023-02148-y
- Khan, N. A., Khan, S. U., Ahmed, S., Farooqi, I. H., Dhingra, A., Hussain, A., et al. (2019). Applications of nanotechnology in water and wastewater treatment: a review. *Asian J. Water, Environ. Pollut.* 16 (4), 81–86. doi:10.3233/ajw190051
- Khan, Z., Thounaojam, T. C., Chowdhury, D., and Upadhyaya, H. (2023). The role of selenium and nano selenium on physiological responses in plant: a review. *Plant Growth Regul.* 100 (2), 409–433. doi:10.1007/s10725-023-00988-0
- Kumar, M., Dwivedi, S., Singh, R. P., Chakrabarty, D., Mallick, S., Trivedi, P. K., et al. (2014). Evaluation of amino acid profile in contrasting arsenic accumulating rice genotypes under arsenic stress. *Biol. Plant.* 58 (4), 733–742. doi:10.1007/s10535-014-0437-2
- Kumar, P., Pandhi, S., Mahato, D. K., Kamle, M., and Mishra, A. (2021). Bacillus-based nano-bioformulations for phytopathogens and insect-pest management. *Egypt. J. Biol. Pest Control* 31, 128. doi:10.1186/s41938-021-00476-w
- Kurimella, V. R., Sanasi, P. D., and Bathula, V. R. (2013). *A novel synthesis of selenium nanoparticles*. Andhra University Research Publications.
- Lazcano-Ramírez, H. G., Garza-García, J. J. O., Hernández-Díaz, J. A., León Morales, J. M., Macías-Sandoval, A. S., and García-Morales, S. (2023). Antifungal activity of selenium nanoparticles obtained by plant mediated synthesis. *Antibiot. (Basel)* 12, 115. doi:10.3390/antibiotics12010115
- Li, D., An, Q., Wu, Y., Li, J.-Q., and Pan, C. (2020). Foliar application of selenium-nanoparticles on celery stimulates several nutrient component levels by regulating the alpha-linolenic acid pathway. *ACS Sustain. Chem. and Eng.* 8, 10502–10510. doi:10.1021/acssuschemeng.0c02819
- Li, S., Chen, H., Jiang, S., Hu, F., Xing, D., and Du, B. (2023). Selenium and nitrogen fertilizer management improves potato root function, photosynthesis, yield and selenium enrichment. *Sustainability* 15 (7), 6060.
- Li, D., Zhou, C., Ma, J., Wu, Y., Kang, L., An, Q., et al. (2021). Nanoselenium transformation and inhibition of cadmium accumulation by regulating the lignin biosynthetic pathway and plant hormone signal transduction in pepper plants. *J. Nanobiotechnology* 19, 316. doi:10.1186/s12951-021-01061-6
- Li D. D., Zhou, C., Wu, Y., An, Q., Zhang, J., Fang, Y., et al. (2022). Nanoselenium integrates soilpepper plant homeostasis by recruiting rhizosphere-beneficial microbiomes and allocating signaling molecule levels under Cd stress. *J. Hazard. Mater.* 432, 128763. doi:10.1016/j.jhazmat.2022.128763
- Li L. L., Liu, Z., Quan, J., Sun, J., Lu, J., and Zhao, G. (2022). Comprehensive proteomic analysis to elucidate the anti-heat stress effects of nano-selenium in rainbow trout (*Oncorhynchus mykiss*). *Ecotoxicol. Environ. Saf.* 241, 113736. doi:10.1016/j.ecoenv.2022.113736
- Liang, Y., Su, Y., Li, L., Huang, X., Panhwar, F. H., Zheng, T., et al. (2019). Quick selenium accumulation in the selenium-rich rice and its physiological responses in changing selenium environments. *BMC Plant Biology* 19 (1), 559. doi:10.1186/s12870-019-2163-6
- Lin, Y., Cao, S., Wang, X., Liu, Y., Sun, Z., Zhang, Y., et al. (2024). Foliar application of sodium selenite affects the growth, antioxidant system, and fruit quality of strawberry. *Front. Plant Sci.* 15, 1449157. doi:10.3389/fpls.2024.1449157
- Liu, H., Fu, Y., Hu, D., Yu, J., and Liu, H. (2018). Effect of green, yellow and purple radiation on biomass, photosynthesis, morphology and soluble sugar content of leafy lettuce via spectral wavebands “knock out”. *Sci. Horticulturae* 236, 10–17. doi:10.1016/j.scienta.2018.03.027
- Liu, K., Li, S., Han, J., Zeng, X., Ling, M., Mao, J., et al. (2021). Effect of selenium on tea (*Camellia sinensis*) under low temperature: changes in physiological and biochemical responses and quality. *Environ. Exp. Bot.* 188, 104475. doi:10.1016/j.envexpbot.2021.104475
- Liu, H., Xiao, C., Qiu, T., Deng, J., Cheng, H., Cong, X., et al. (2022). Selenium regulates antioxidant, photosynthesis, and cell permeability in plants under various abiotic stresses: a review. *Plants* 12 (1), 44. doi:10.3390/plants12010044
- Lowry, G. V., Avellan, A., and Gilbertson, L. M. (2019). Opportunities and challenges for nanotechnology in the agri-tech revolution. *Nat. Nanotechnology* 14 (6), 517–522. doi:10.1038/s41565-019-0461-7
- Malik, J. A., Kumar, S., Thakur, P., Sharma, S., Kaur, N., Kaur, R., et al. (2011). Promotion of growth in mungbean (*Phaseolus aureus* roxb.) by selenium is associated with stimulation of carbohydrate metabolism. *Biol. Trace Elem. Res.* 143 (1), 530–539. doi:10.1007/s12011-010-8878-9
- Nandini, B., Hariprasad, P., Prakash, H. S., Shetty, H. S., and Geetha, N. (2017). Trichogenic-selenium nanoparticles enhance disease suppressive ability of trichoderma against downy mildew disease caused by *Sclerosporagrammicola* in pearl millet. *Sci. Rep.* 7, 2612. doi:10.1038/s41598-017-02737-6
- Narayanan, K. B., and Sakthivel, N. (2010). Biological synthesis of metal nanoparticles by microbes. *Adv. Colloid Interface Science* 156 (1–2), 1–13. doi:10.1016/j.cis.2010.02.001
- Nasiri, Y., Asadi, M., Zahedi, S. M., and Venditti, A. (2025). Selenium nanoparticles improved biochemical and physiological properties and antioxidant systems of savoury under drought stress. *Nat. Prod. Res.* 39 (5), 1188–1198. doi:10.1080/14786419.2023.2299303

- Nedjimi, B. (2025). The role of selenium and selenium nanoparticles in enhancing plant tolerance to cadmium stress: a sustainable approach. *Discov. Plants* 2 (1), 1–22. doi:10.1007/s44372-025-00215-2
- Omar, A. A., Heikal, Y. M., Zayed, E. M., Shamseldin, S. A., Salama, Y. E., Amer, K. E., et al. (2023). Conferring of drought and heat stress tolerance in wheat (*Triticum aestivum* L.) genotypes and their response to selenium nanoparticles application. *Nanomaterials* 13 (6), 998. doi:10.3390/nano13060998
- Perilla-Henao, L. M., and Casteel, C. L. (2016). Vector-borne bacterial plant pathogens: interactions with hemipteran insects and plants. *Front. Plant Sci.* 7, 1163. doi:10.3389/fpls.2016.01163
- Perumal, S., Gopal Samy, M. V., and Subramanian, D. (2021). Selenium nanoparticle synthesis from endangered medicinal herb (*Enicostema axillare*). *Bioprocess Biosyst. Eng.* 44 (6), 1185–1196. doi:10.1007/S00449-021-02565-Z
- Pezzarossa, B., Remorini, D., Gentile, M. L., and Massai, R. (2012). Effects of foliar and fruit addition of sodium selenate on selenium accumulation and fruit quality. *J. Sci. Food Agric.* 92 (4), 781–786. doi:10.1002/jsfa.4644
- Pickering, I. J., Prince, R. C., Salt, D. E., and George, G. N. (2000). Quantitative, chemically specific imaging of selenium transformation in plants. *Proc. Natl. Acad. Sci.* 97 (20), 10717–10722. doi:10.1073/pnas.200244597
- Pilon-Smits, E. A. H., and Quinn, C. F. (2010). "Selenium metabolism in plants," in *Cell biology of metals and nutrients*. Editors R. Hell, and R. R. Mendel (Springer), 225–241. doi:10.1007/978-3-642-10613-2_10
- Qi, W. Y., Li, Q., Chen, H., Liu, J., Xing, S. F., Xu, M., et al. (2021). Selenium nanoparticles ameliorate Brassica napus L. cadmium toxicity by inhibiting the respiratory burst and scavenging reactive oxygen species. *J. Hazard. Mater.* 417, 125900. doi:10.1016/j.jhazmat.2021.125900
- Qin, X., Wang, Z., Lai, J., Liang, Y., and Qian, K. (2025). The synthesis of selenium nanoparticles and their applications in enhancing plant stress resistance: a review. *Nanomaterials* 15 (4), 301. doi:10.3390/nano15040301
- Rady, M. M., Desoky, E. S. M., Ahmed, S. M., Majrashi, A. A., Ali, E. F., Arnout, S. M., et al. (2021). Foliar nourishment with nano-selenium dioxide promotes physiology, biochemistry, antioxidant defenses, and salt tolerance in *Phaseolus vulgaris*. *Plants* 10 (6), 1189. doi:10.3390/plants10061189
- Rahman, M., Rahman, K., Sathi, K. S., Alam, M. M., Nahar, K., Fujita, M., et al. (2021). Supplemental selenium and boron mitigate salt-induced oxidative damages in *Glycine max* L. *Plants* 10 (10), 2224.
- Rahmanto, A. S., and Davies, M. J. (2011). Catalytic activity of selenomethionine in removing amino acid, peptide, and protein hydroperoxides. *Free Radic. Biol. Med.* 51 (12), 2288–2299. doi:10.1016/j.freeradbiomed.2011.09.027
- Raliya, R., Saharan, V., Dimkpa, C., and Biswas, P. (2017). Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. *J. Agricultural Food Chemistry* 66 (26), 6487–6503. doi:10.1021/acs.jafc.7b02178
- Ramezan, D., Zargar, M., Nakhaev, M. R., Said-Akhmadovich, K. A., Bayat, M., and Ghaderi, A. (2024). Selenium alleviates growth characteristics, plant pigments, photosynthetic and antioxidant capacity of basil (*Ocimum basilicum* L.) under low temperature. *Biocatal. Agric. Biotechnol.* 58, 103198. doi:10.1016/j.cbab.2024.103198
- Ramos, D. P., Chan, G. A. H., Dias, M. A. R., Silva, D. V., Sousa, P. L. R., Júnior, N. R. M., et al. (2023). Effect of foliar application with selenium on biofortification and physiological attributes of irrigated rice cultivars. *J. Food Compos. Analysis* 123, 105534. doi:10.1016/j.jfca.2023.105534
- Ran, M., Wu, J., Jiao, Y., and Li, J. (2024). Biosynthetic selenium nanoparticles (Bio-SE-NPs) mitigate the toxicity of antimony (Sb) in rice (*Oryza sativa* L.) by limiting Sb uptake, improving antioxidant defense system and regulating stress-related gene expression. *J. Hazard. Mater.* 470, 134263.
- Rashid, M. T., Liu, K., Ning, M., Ullah, K., Wali, A., Jatoti, M. A., et al. (2024). Enhanced antioxidant activity of selenium-enriched brown rice protein against oxidative stress in Mammalian erythrocytes under various cooking conditions. *J. Agric. Food Res.* 18, 101520. doi:10.1016/j.jafr.2024.101520
- Saleem, M. F., Kamal, M. A., Shahid, M., Awais, M., Saleem, A., Raza, M. S., et al. (2021). Studying the foliar selenium-modulated dynamics in phenology and quality of terminal heat-stressed cotton (*Gossypium hirsutum* L.) in association with yield. *Plant Systems-An International Journal Dealing with all Aspects of Plant Biology* 155 (4), 668–678.
- Sampath, S., Sunderam, V., Manjusha, M., Dlamini, Z. L., and Lawrance, A. V. (2024). Selenium nanoparticles: a comprehensive examination of synthesis techniques and their diverse applications in medical research and toxicology studies. *Molecules* 29 (4), 801. doi:10.3390/molecules29040801
- Sarkar, J., Mridha, D., Davoodbasha, M. A., Banerjee, J., Chanda, S., Ray, K., et al. (2023). A state-of-the-art systemic review on selenium nanoparticles: mechanisms and factors influencing biogenesis and its potential applications. *Biol. Trace Elem. Res.* 201 (10), 5000–5036. doi:10.1007/s12011-022-03549-0
- Sarwar, N., Akhtar, M., Kamran, M. A., Imran, M., Riaz, M. A., and Kamran, K. (2020). Selenium nanoparticles as a nutritional supplement. *Nutrition* 33, 83–90.
- Sayed, E. G., Desoukey, S. F., Desouky, A. F., Farag, M. F., El-Kholy, R. I., and Azoz, S. N. (2024). Synergistic influence of arbuscular mycorrhizal fungi inoculation with nanoparticle foliar application enhances chili (*Capsicum annum* L.) antioxidant enzymes, anatomical characteristics, and productivity under cold-stress conditions. *Plants* 13 (4), 517. doi:10.3390/plants13040517
- Schiavon, M., and Pilon-Smits, E. A. (2017). The fascinating facets of plant selenium accumulation—biochemistry, physiology, evolution and ecology. *New Phytol.* 213 (4), 1582–1596. doi:10.1111/nph.14378
- Schiavon, M., dall'Acqua, S., Mietto, A., Pilon-Smits, E. A., Sambo, P., Masi, A., et al. (2013). Selenium fertilization alters the chemical composition and antioxidant constituents of tomato (*Solanum lycopersicon* L.). *J. Agric. Food Chem.* 61 (44), 10542–10554. doi:10.1021/jf4031822
- Schiavon, M., Berto, C., Malagoli, M., Trentin, A., Sambo, P., Dall'Acqua, S., et al. (2016). Selenium biofortification in radish enhances nutritional quality via accumulation of methyl-selenocysteine and promotion of transcripts and metabolites related to glucosinolates, phenolics, and amino acids. *Front. Plant Sci.* 7, 1371. doi:10.3389/fpls.2016.01371
- Schwab, F., Zhai, G., Kern, M., Turner, A., Schnoor, J. L., and Wiesner, M. R. (2016). Barriers, pathways and processes for uptake, translocation and accumulation of nanomaterials in plants—critical review. *Nanotoxicology* 10 (3), 257–278. doi:10.3109/17435390.2015.1048326
- Serov, D. A., Khabatova, V. V., Vodeneev, V., Li, R., and Gudkov, S. V. (2023). A review of the antibacterial, fungicidal and antiviral properties of selenium nanoparticles. *Materials* 16 (15), 5363. doi:10.3390/ma16155363
- Serrano-Sandoval, S. N., Guardado-Félix, D., and Gutiérrez-Urbe, J. A. (2022). Deglycosylation of isoflavones in selenized germinated chickpea flours due to convection drying. *LWT* 153, 112417. doi:10.1016/j.lwt.2021.112417
- Shahbaz, M., Akram, A., Raja, N. I., Mukhtar, T., Mehak, A., Fatima, N., et al. (2023). Antifungal activity of green synthesized selenium nanoparticles and their effect on physiological, biochemical, and antioxidant defense system of mango under mango malformation disease. *PLoS One* 18 (2), e0274679. doi:10.1371/journal.pone.0274679
- Shahid, M. A., Balal, R. M., Khan, N., Zotarelli, L., Liu, G. D., Sarkhosh, A., et al. (2019). Selenium impedes cadmium and arsenic toxicity in potato by modulating carbohydrate and nitrogen metabolism. *Ecotoxicol. Environ. Saf.* 180, 588–599. doi:10.1016/j.ecoenv.2019.05.037
- Shalaby, T. A., Bayoumi, Y., El-Badri, A. M., Taha, N., Alshala, T., El-Ramady, H., et al. (2021). Selenium nanoparticles as a potential candidate for controlling cucumber downy mildew disease. *Environ. Sci. Pollut. Res.* 28 (36), 49935–49950. doi:10.1007/s11356-021-14891-5
- Shang, H., Zhang, H., Zhao, R., Yu, M., Ma, Y., Sun, Z., et al. (2022). Selenium nanoparticles are effective in penetrating pine and causing high oxidative damage to *Bursaphelenchus xylophilus* in pine wilt disease control. *Pest Manag. Sci.* 78 (9), 3704–3716. doi:10.1002/ps.7064
- Sheikhalipour, M., Esmailpour, B., and Gohari, G. (2021). Effects of selenium nanoparticles on antioxidant enzymes and physiological traits in salt-stressed common bean (*Phaseolus vulgaris* L.). *Sci. Hortic.* 285, 110196. doi:10.1016/j.scienta.2021.110196
- Shi, T., Wang, Y., Li, Y., Sui, X., and Dong, C. H. (2024). Generation of selenium-rich wheat mutants and exploration of responsive genes for selenium accumulation. *Plant cell rep.* 43 (5), 132.
- Singhal, R. K., Fahad, S., Kumar, P., Choyal, P., Javed, T., Jinger, D., et al. (2023). Beneficial elements: new players in improving nutrient use efficiency and abiotic stress tolerance. *Plant Growth Regul.* 100 (2), 237–265. doi:10.1007/s10725-022-00843-8
- Skalickova, S., Milosavljevic, V., Cihalova, K., Horky, P., Richtera, L., and Adam, V. (2017). Selenium of agricultural and food chemistry, 69(51), 15458–15467.
- Skrypnik, L., Novikova, A., and Tokupova, E. (2019). Improvement of phenolic compounds, essential oil content and antioxidant properties of sweet basil (*Ocimum basilicum* L.) depending on type and concentration of selenium application. *Plants* 8 (11), 458. doi:10.3390/plants8110458
- Soliman, M. H., Omar, S. A., Elkesh, A., and Abdelaal, K. A. A. (2023). Selenium nanoparticles improve the tolerance of cucumber plants to combined salinity and heat stress. *Plant Physiology Biochem.* 195, 53–62. doi:10.1016/j.plaphy.2023.04.016
- Suseela, V., Tharayil, N., Xing, B., and Dukes, J. S. (2014). Warming and drought differentially influence the production and resorption of elemental and metabolic nitrogen pools in *Quercus rubra*. *Glob. Change Biol.* 20 (11), 3529–3542. doi:10.1111/gcb.12634
- Szöllösi, R., Molnár, Á., Oláh, D., Kondak, S., and Kolbert, Z. (2022). "Uptake and metabolism of selenium in plants: recent progress and future perspectives," in *Selenium and nano-selenium in environmental stress management and crop quality improvement*, 79–90.
- Taha, N. A., Hamden, S., Bayoumi, Y. A., Elshakhawy, T., El-Ramady, H., and Solberg, S. Ø. (2023). Nanofungicides with selenium and silicon can boost the growth and yield of common bean (*Phaseolus vulgaris* L.) and control *Alternaria* leaf spot disease. *Microorganisms* 11 (3), 728.
- Tang, Y., He, G., Guo, Z., Su, M., Liu, P., Song, Y., et al. (2022). Biological nano-selenium foliar application reduces cadmium accumulation in peppers through concentration-dependent regulation.
- Terry, N., Zayed, A. M., de Souza, M. P., and Tarun, A. S. (2000). Selenium in higher plants. *Annu. Rev. Plant Biol.* 51 (1), 401–432. doi:10.1146/annurev.arplant.51.1.401

- Tian, M., Xu, X., Liu, Y., Xie, L., and Pan, S. (2016). Effect of Se treatment on glucosinolate metabolism and health-promoting compounds in the broccoli sprouts of three cultivars. *Food Chem.* 190, 374–380. doi:10.1016/j.foodchem.2015.05.117
- Wadhvani, S. A., Shedbalkar, U. U., Singh, R., and Chopade, B. A. (2016). Biogenic selenium nanoparticles: current status and future prospects. *Appl. Microbiology Biotechnology* 100 (6), 2555–2566. doi:10.1007/s00253-016-7300-7
- Wang, K., Wang, Y., Li, K., Wan, Y., Wang, Q., Zhuang, Z., et al. (2020). Uptake, translocation and biotransformation of selenium nanoparticles in rice seedlings (*Oryza sativa L.*). *J. Nanobiotechnology* 18 (1), 103.
- Winkel, L. H., Vriens, B., Jones, G. D., Schneider, L. S., Pilon-Smits, E., and Bañuelos, G. S. (2015). Selenium cycling across soil-plant-atmosphere interfaces: a critical review. *Nutrients* 7 (6), 4199–4239. doi:10.3390/nu7064199
- Xia, Q., Yang, Z., Shui, Y., Liu, X., Chen, J., Khan, S., et al. (2020). Methods of selenium application differentially modulate plant growth, selenium accumulation and speciation, protein, anthocyanins and concentrations of mineral elements in purple-grained wheat. *Front. Plant Sci.* 11, 1114. doi:10.3389/fpls.2020.01114
- Xin, T. Z., Fu, Y., Wang, X. S., Jiang, N., Zhai, D. D., Shang, X. D., et al. (2025). Research progress of selenium-enriched edible fungi. *Horticulturae* 11 (5), 531. doi:10.3390/horticulturae11050531
- Xu, J., Jia, W., Hu, C., Nie, M., Ming, J., Cheng, Q., et al. (2020). Selenium as a potential fungicide could protect oilseed rape leaves from *Sclerotinia sclerotiorum* infection. *Environ. Pollut.* 257, 113495. doi:10.1016/j.envpol.2019.113495
- Yuan, S., Zhang, Y., Dong, P. Y., Yan, Y. M. C., Liu, J., Zhang, B. Q., et al. (2024). A comprehensive review on potential role of selenium, selenoproteins and selenium nanoparticles in Male fertility. *Heliyon* 10 (15), e34975. doi:10.1016/j.heliyon.2024.e34975
- Zafar, S., Ashraf, M. Y., Niaz, M., and Rehman, S. (2024). Selenium nanoparticles modulate physiological and biochemical responses of bitter melon under salt stress. *J. Plant Physiology* 285, 153096. doi:10.1016/j.jplph.2023.153096
- Zeeshan, M., Qureshi, R., and Iqbal, M. (2024). Foliar application of selenium nanoparticless improves drought tolerance in wheat. *Environ. Sci. Pollut. Res.* 31 (5), 6328–6340. doi:10.1007/s11356-023-29741-8
- Zhang P. P., Guo, Z., Zhang, Z., Fu, H., White, J. C., and Lynch, I. (2020). Nanomaterial transformation in the soil-plant system: implications for food safety and application in agriculture. *Small* 16 (21), 2000705. doi:10.1002/sml.202000705
- Zhang X, X., He, H., Xiang, J., Yin, H., and Hou, T. (2020). Selenium-containing proteins/peptides from plants: a review on the structures and functions. *J. Agric. Food Chem.* 68 (51), 15061–15073. doi:10.1021/acs.jafc.0c05594
- Zhang, T., Qi, M., Wu, Q., Xiang, P., Tang, D., and Li, Q. (2023). Recent research progress on the synthesis and biological effects of selenium nanoparticles. *Front. Nutrition* 10, 1183487. doi:10.3389/fnut.2023.1183487
- Zhang, W., Zhang, F., Wang, Y., Wang, J., Liu, J., Zhang, H., et al. (2025). A review of geological characteristics and selenium enrichment in Se-bearing volcanogenic massive sulfide deposits. *Int. Geol. Rev.* 67 (10), 1306–1321. doi:10.1080/00206814.2024.2434873
- Zhao, S., Zhou, Y., Yang, X., Fan, Z., Li, F., Yuan, T., et al. (2023). Effect of selenium and sulfur interaction on the glucosinolate content and antioxidant activity of sprouts of Chinese cabbage. *Food Sci.* 44 (22), 29–36.
- Zhou, J., Zhang, C., Du, B., Cui, H., Fan, X., Zhou, D., et al. (2021). Soil and foliar applications of silicon and selenium effects on cadmium accumulation and plant growth by modulation of antioxidant system and Cd translocation: comparison of soft vs. durum wheat varieties. *J. Hazard. Mater.* 402, 123546. doi:10.1016/j.jhazmat.2020.123546
- Zhou, Y., Nie, K., Geng, L., Wang, Y., Li, L., and Cheng, H. (2024). Selenium's role in plant secondary metabolism: regulation and mechanistic insights. *Agronomy* 15 (1), 54. doi:10.3390/agronomy15010054
- Zhu, Y., Dong, Y., Zhu, N., and Jin, H. (2022). Foliar application of biosynthetic nano-selenium alleviates the toxicity of Cd, Pb, and Hg in Brassica chinensis by inhibiting heavy metal adsorption and improving antioxidant system in plant. *Ecotoxicol. Environmental Safety* 240, 113681. doi:10.1016/j.ecoenv.2022.113681